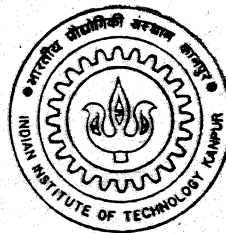# A DECISION SUPPORT SYSTEM
for
POWDER METALLURGY PROCESSING

by

AJAY KUMAR DAS

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

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A
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for
POWDER METALLURGY PROCESSING

A thesis submitted

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for the degree of
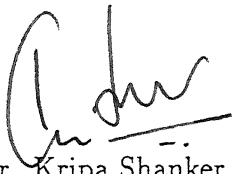
MASTER OF TECHNOLOGY

by

Ajay Kumar Das [9310503]

to the

Department of Mechanical Engineering
INDIAN INSTITUTE of TECHNOLOGY, KANPUR

1995.

CERTIFICATE

This is to certify that the work contained in this thesis entitled "**A Decision Support System for Powder Metallurgy Processing**", by Ajay Kumar Das, has been carried out under our supervision and has not been submitted elsewhere for award of a degree.

Dr. Kripa Shanker

Professor

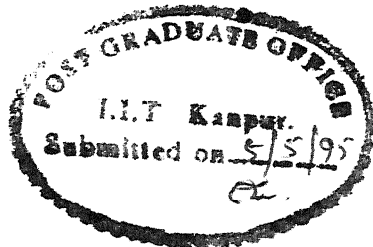Industrial & Management Engg. Dept.

IIT, Kanpur.
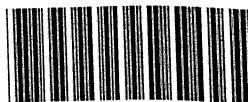

Dr. G. K. Lal

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Submitted on 5/5/95

Abstract

This thesis is an attempt to develop a decision support system for the powder metallurgy processing.

The system acts as a guide in the selection process of the various stages of powder metallurgy processing. The system incorporates three major stages of the powder metallurgy processing—powder selection, compaction and sintering.

Powder selection module is concerned with the selection of the powder. In the compaction module the activities include selection of suitable pressure, the calculation of die and core–rod diameter and the selection of the press. In the sintering module the concern is primarily to select optimal values of sintering temperature and sintering time. The system currently handles the cylindrical (solid and hollow) parts.

A simulation of the process and the state(dimensions) of the part at various stages of the process is done.

The prime feature of the system is its high interactiveness with the objective of less embarassment to the user. The system is totally menu driven and has been implemented in the C programming language in Unix environment. HP Starbase library has been used for the graphics portion. The software is implemented on the HP workstations in Computer Centre I.I.T. Kanpur.

to. . .

"You are not poor if
You have a DREAM"

SUSHMITA

ACKNOWLEDGEMENT

I express my deep gratitude and sincere regards to my thesis supervisors, Dr. G. Lal and Dr. Kripa Shanker for their constant inspiration, encouragement and idance throughout the work.

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For the software part I am thankful to Mr. K. Srinivasa Rao (Project Associate, ptt. of MEM) who would often sit with me before the terminal and help debug the ,gram. My learning of the language C is also largely due to him and Rambhusan rawal.

My stay at IIT Kanpur would not have been as meaningful as it was, had I not n a member of the P. G. Counselling Service Movement. It taught me all those ;he essence of a complete man.

My regards are also due to the P. G. Mechanical Gang and all my well wishers , made my stay at IIT Kanpur a memorable one.

<div align="right">Ajay Kumar Das</div>

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Chapter 1

Introduction

A decision support system is an interactive computer based system which helps decision makers utilize data and models to solve unstructured problems.

The characteristics of a decision support system normally are :

- they are computer based systems,

- they help decision makers,

- tackle ill structured problems,

- they have direct interaction with user,

- they use data and analysis models.

Powder metallurgy is an unstructured process in that there is no systematic way to fix the values of its various process parameters. A decision support system may be of some help to such unstructured process.

Powder metallurgy involves several stages wherein powders are gradually converted to the required part. Each of these stages is marked with some process characterizing parameters. There are no sharp values for these parameters and they can assume any value within a range of values. Very often they are decided on by striking

1

off a balance between the two contrasting characteristics—*quality* and *cost*. Thus each stage is marked with some decision variables.

In powder metallurgy the process variables are so many that it is extremely difficult to account for all of them and very often they are actually decided on the basis of experience and the past behaviour. It is in this respect a decision support system might be useful wherein the final selection is left to the user — the computer taking care of accountable factors and the user, from his experience, some of the factors not accounted for in the system. By combining the consideration of accountable factors and the experience of the personnel a good decision may be arrived at.

The prime objective here is to have a methodology by which the three major process variables—compaction pressure, sintering temperature and sintering time can be decided upon.

The selection of compaction pressure depends on the principle of minimum density rise per unit increase in pressure. The selection of sintering temperature and sintering time is based on the principle of least total heat requirement.

A brief introduction to powder metallurgy processing is given in chapter2.

1.1   Literature Survey

A systematic approach at the macroscopic level for powder metallurgy has received very less attention. Most of the literature has its focus on the microscopic nature of the process.

Fleck and *Smith* discuss the simple brick model to estimate the effect of density upon the ultimate tensile strength of the material.

R.M.German [1989] talks of the mechanism of particle packing and also discusses the relation of relative density and compaction pressure used during compaction.

V.A.Ivensen [1973] gives an indepth mathematical analysis of the sintering of single phase powders.

R.M.German [1984] discusses various aspects of powder metallurgy processing qualitatively.

1.2 Thesis Organization

Chapter 2 is a nutshell representation of powder metallurgy processing. Although written very brief it extends over few pages and so has been made a separate chapter.

Chapter 3 titled *Systems Analysis* discusses the various elements of the system. The elements and their analysis have been discussed in various sections.

Chapter 4 explains the implementation part of the system. It shows how various elements discussed in *chapter 3* have been made use of to obtain an objective.

Chapter 5 is a discussion of two particular cases of the many parts hypothetically made by the system.

Chapter 6 provides a gist of the present work and a thorough description of its limitation which can be taken up in future work.

Chapter 2

Powder Metallurgy : A Brief Outline

The term *powder metallurgy* is defined as the material processing technique used to consolidate particulate matters into discrete shapes. Among the various metal working technologies, powder metallurgy is the most diverse manufacturing approach.

Raw powders having the desired size, shape and other characteristics of importance are either blended by themselves or with additives such as lubricants or alloy additions in a device which ensures the production of a homogeneous powder or mix. The powder is then compacted under pressure within a rigid die at room temperature. The process is known as *compaction*. Compaction is done to consolidate and densify the loose powder into a green compact that has sufficient strength for handling. The desired size and shape of the product are basically determined in this step. The green compact is then heated in a furnace at a relatively high temperature. The process is better known as *sintering*. In most cases it is a solid state process. One of the most important results of sintering is the development of the chemical and metallurgical bonds among the original particles. This leads to the attainment of integrity and a high level of strength in the compact.

After sintering the part may be ready for use or secondary operations such as

```
┌─────────────────────────┐
│      METAL POWDER       │
└─────────────────────────┘
             │
             ▼
┌─────────────────────────┐
│                         │ ◄──────── LUBRICANTS
│        BLENDING         │
│                         │ ◄──────── ALLOY ADDITIONS
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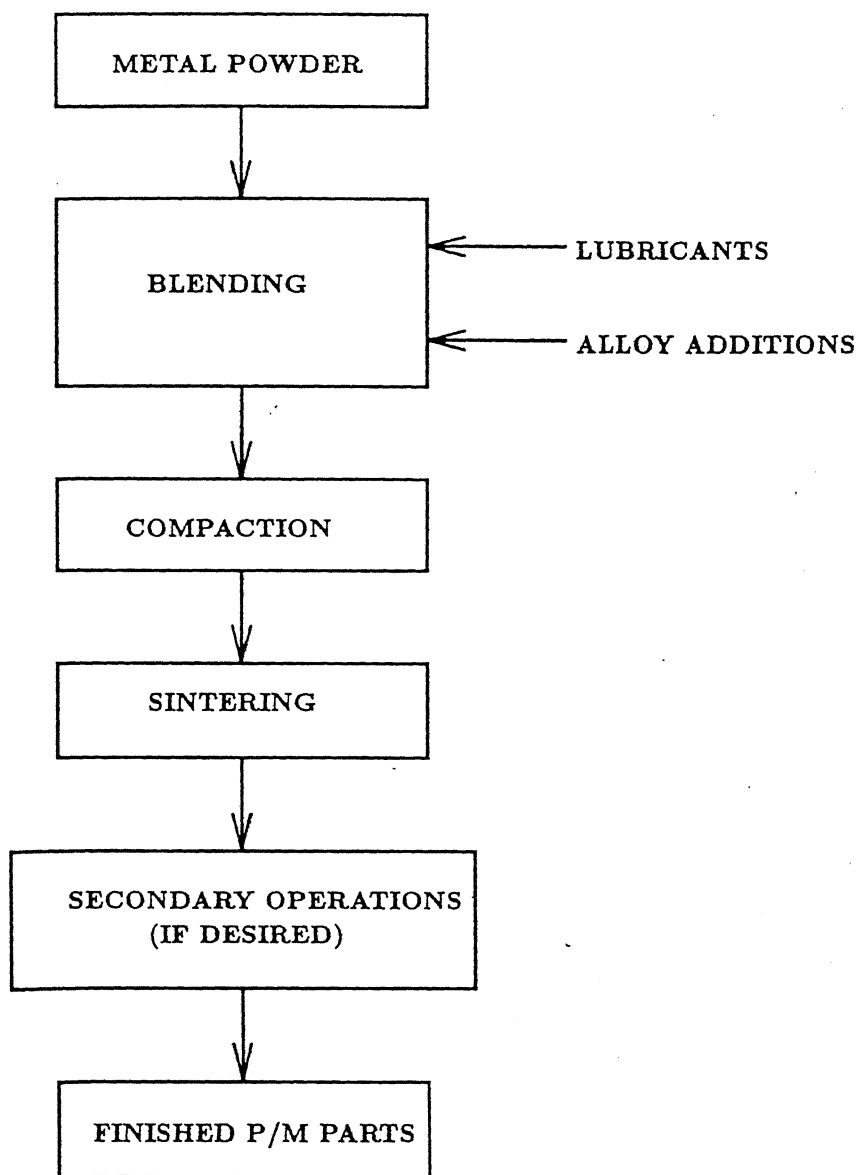
Figure 2.1: Various stages in powder metallurgy processing.

repressing, infiltration with a molten metal or impregnation with plastic or liquid lubricant to achieve specific properties. Operations like machining, tumbling, heat treatment may also be carried out. Various stages involved in a powder metallurgy process is shown in figure 2.1.

Two very important factors in relation to powder metallurgy worth noticing are :

1. The process offers the greatest economic advantage when very few secondary operations are necessary; and large quantities of a part may be mass produced at rapid rates.

2. The process variables may be adjusted to produce parts with controllable types and amounts of useful porosity or with densities approaching the theoretical value that are analogous to and competitive with conventional cast and wrought materials.

The major steps involved in the process are discussed in the following sections.

2.1 Powder Compaction

Compaction of powders has the following major functions :

1. To consolidate the powder into desired shape.

2. To impart to as high a degree as possible, the desired final dimensions with due consideration to any dimensional changes resulting from sintering.

3. To impart the desired level and type of porosity.

4. To impart adequate strength for subsequent handling.

The major compaction processes are :

1. Pressure techniques :

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The major compaction processes are :

1. Pressure techniques :

- Die.

- Isostatic.

- High energy rate forming (HERF).

- Forging.

- Extrusion.

- Vibratory.

- Continuous.

2. Pressureless techniques :

- Slip casting.

- Gravity.

Die compaction being the most common of these techniques is discussed here in brief.

2.1.1   Die Compaction

This is most widely used method and considered as the conventional technique. It applies either low or very high pressure, allows pressure to be applied only in the axial direction to one or both ends of the powder, involves relatively low speeds. Die used is a rigid solid mass. The basic components are :

1. Source of energy or pressure – usually mechanical or hydraulic mechanism.

2. Die of proper strength.

3. Upper and lower punches of the proper strength and design to contain powder, apply pressure and assist in part removal or ejection.

4. Core rods for the formation of holes.

5. Proper controls and instrumentation.

Two different types of die compaction techniques are :

1. Single action compaction – has only one dynamic pressing action. The upper punch enters the die cavity, compresses the powder against the stationary lower punch, inner surface of the die cavity and external surface of core rods (if any) present. Pressures may be applied through hydraulic or mechanical (cam, lever, toggle, crank) mechanism. This technique is used to produce relatively thin types of parts.

2. Double action compaction – signifies that the powder is compacted simultaneously from both directions by both the lower and upper punches. Core rods may be stationary or movable. This technique may be used to produce parts over a broad thickness range.

Green Compact Density

The density of the as compacted material is one of the most useful properties in powder metallurgy. It is a measure of the effectiveness of the compaction and also determines behaviour of the material during subsequent sintering.

Although it is customary to deal with single values of green density, in compacts there is actually a density distribution. The density distribution results from stress distribution within the compact and the later result chiefly from frictional forces developed at the die wall. Although a certain load is applied to the powder in the die, some fraction of this load is transferred to the die wall because of the friction developed there – the movement of the particle being inhibited by the die surface and other particles. Particles near the punch surface move rather easily. This is particularly true in the central region, away from the die wall. This results in high densities and increased particle-die wall contact and frictional forces in the outer

regions. As compaction continues the particles farthest away from the punch move smaller distances and more porosity is retained in those regions.
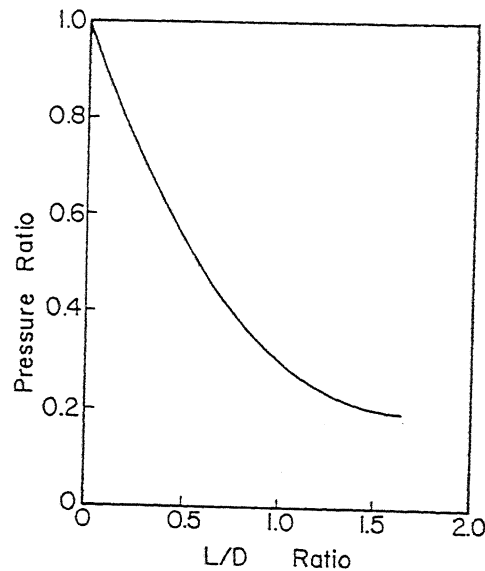
Figure 2.2: Effect of L/D ratio on the pressure transmitted.

A green density distribution is very much dependent on the (L/D) ratio of the compact. If the (L/D) ratio is reduced then the density distribution is minimized. This happens because by decreasing the ratio, the volume of the compact farthest away from the source of pressure is reduced. Figure 2.2[1] shows that as L/D ratio increases the pressure obtained at a point farthest away from the source of pressure is reduced.

Variations in green density distribution within a given compact can be minimized by the use of the following procedures :

1. Using lubricants to reduce die wall friction.

2. Using high pressures.

3. Using low (L/D) ratios.

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[1] Taken from *Introduction to Powder Metallurgy*, Hirschhorn,J.S., page–136.

4. Using double action compaction.

Various theories and mathematical analyses have been proposed to describe quantitatively the compaction process in terms of the dependence of the green density on compaction pressure and possibly some other factors. Such analyses really neglect the density distribution problem. No one equation has been formulated which has universal application. This is not unexpected since the behaviour of the powder during compaction can be highly complex and will be influenced by many factors, including properties of the powdered material and geometrical process parameters. In general there can be two well defined parts of the density–pressure curves. An early low pressure stage where plastic deformation is relatively unimportant and particle movement dominates the densification process, and a second stage where deformation and possibly fracture is the critical mechanism.

2.2 Sintering

Compaction provides the basic shape to metal powders, but the resulting properties in the green state are unattractive. *Sintering* provides thermal energy to initiate interparticle welds and improve the properties. The sintering of green compacts is a very complex process. The subject of sintering is best approached from the viewpoint that any green compact or mass of lose powder is at the very least a two phase material – porosity and solid material. Each has its own morphology – *i.e.*, size, shape, distribution and amount.

Sintering may be considered the process by which an assembly of particles compacted under pressure or simply confined in a container, chemically bond themselves into a coherent body under the influence of an elevated temperature. The sintered material is analogous to conventional forms of solid material such as castings, forgings etc. Densification or shrinkage of the sintered material is very often associated with all forms of sintering.

Sintering is usually considered a solid state process; *i.e.*, no molten or liquid phase present. Liquid phase sintering refers to those cases for which the sintering temperature is high enough that one or more components of the material is present as a liquid during all or part of the sintering process. The infiltration technique achieves densification without necessarily causing any shrinkage of the original green compact; *i.e.*, the porosity is simply filled up by the infiltrant. In most other cases densification signifies shrinkage resulting from the elimination of porosity.

There has been a great deal of experimental and theoretical work on the fundamental aspects of sintering. However today there is much about the process that is not understood and one universal applicable theory of sintering has not been achieved.

2.2.1   Driving Forces for Sintering

A green compact is basically an unstable material at elevated temperatures. Although there are several major driving forces it is most important to recognize that the major distinction between the sinter mass and other forms of material is the presence of internal surface area associated with the pore–solid interface.

A decrease in surface area corresponds to a decrease in the surface free energy contribution to the total free energy of the system.

The greater the amount of surface area in the original material, the greater is the driving force for sintering.

2.2.2   Effect of Process Variables in Sintering

Temperature

Sintering is extremely dependent of temperature. Increasing the temperature greatly increases the rate and magnitude of any changes occuring. Figure 2.3[2] illustrates the effect of increasing temperature for a constant green density.

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[2]Taken from *Introduction to Powder Metallurgy*, Hirschhorn,J.S., page–204
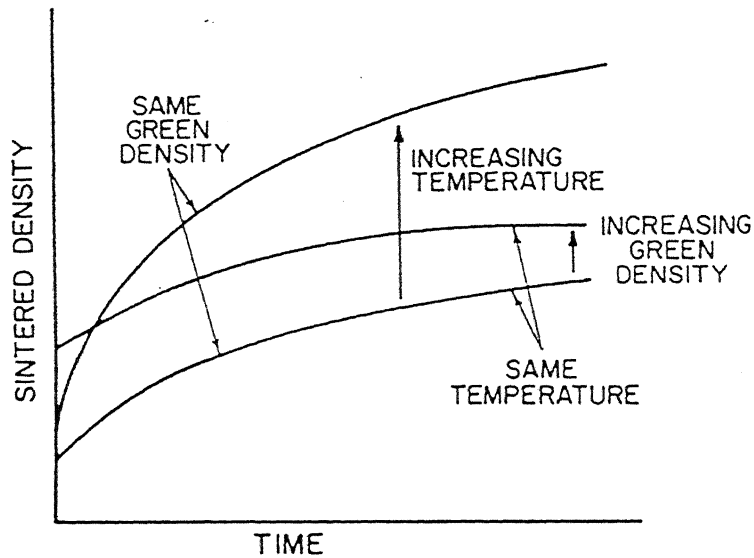
Figure 2.3: Sintered density–time curves.

Time

Although the degree of sintering increases with increasing time, the effect is small in comparison to the temperature dependence. The rate of sintering decreases with increasing time. The largest change comes about in the earliest period of sintering. Tens or hundreds of hours are normally required to affect changes that could be brought about by an increase in sintering temperature of perhaps 100° Fahrenheit — the loss of driving force with increasing time at any temperature is one of the reasons.

2.3   Applications

Powder metallurgy materials range from the most exotic and sophisticated innovations as rockets to parts in our mundane washing machines and automobiles. The materials being processed include our oldest known metals such as iron and copper to the newest alloys, composites and nonmetallic materials.

Chapter 3

Systems Analysis

A system is a collection of related entities with inter–related attributes to meet certain pre-specified goal. This chapter describes the various elements, their subelements and intra–element relationship. The inter relationship of the elements toward the attainment of the goal is discussed in the chapter titled *Implementation*. The goal is to make a part and the elements are powder selection, compaction, sintering and optimization. The present chapter gives a comprehensive discussion on each of these elements in a way they will be used in the system. The section *Density Strength Relationship* is actually the basis of powder selection. The system flow chart is shown in figure 3.1 and 3.2.

3.1 Compaction

When compaction is performed, the principal object is to effect cold-pressure welds between the particles so that some cohesion is conferred.

3.1.1 Density—Pressure Relations
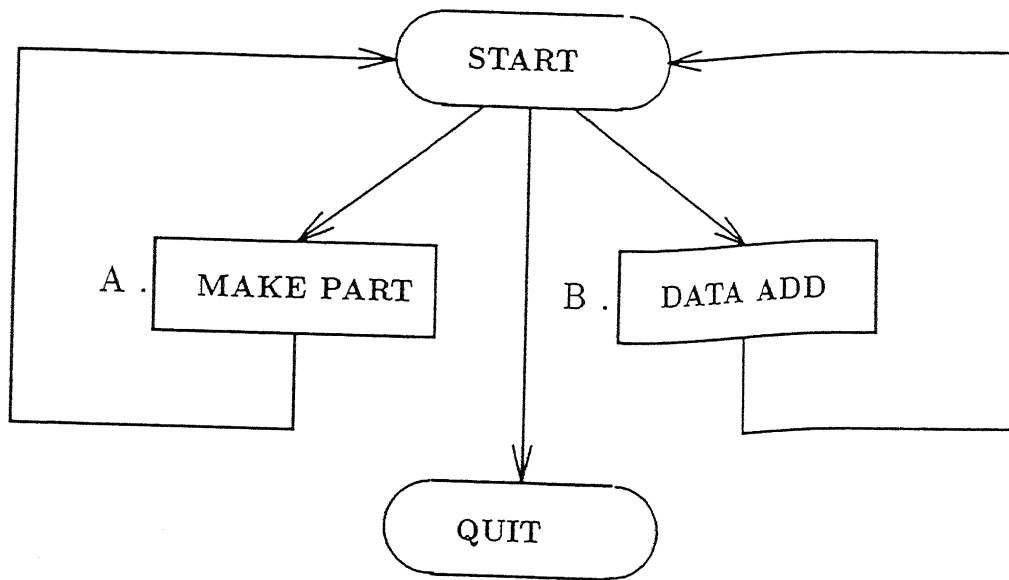
Figure 3.1: Two main parallel module shown in rectangular boxes.

The relation between density and the applied pressure is an important aspect of compaction. A density pressure curve is shown in figure 3.3[1]. As the pressure is increased the compact density increases or alternatively porosity decreases. The response of a particle mass to pressure is termed the compressibility, and is often defined as the density attained at a preset compaction pressure. Various theories of densification during compaction note that the change in fractional density f with pressure P can be expressed as follows :

$$\frac{df}{dP} = K(1 - f) \tag{3.1}$$

where,

K is a proportionality constant and

$(1 - f)$ is the porosity

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[1]Taken from *Particle Packing Characteristics*, R.M.German., page—229.
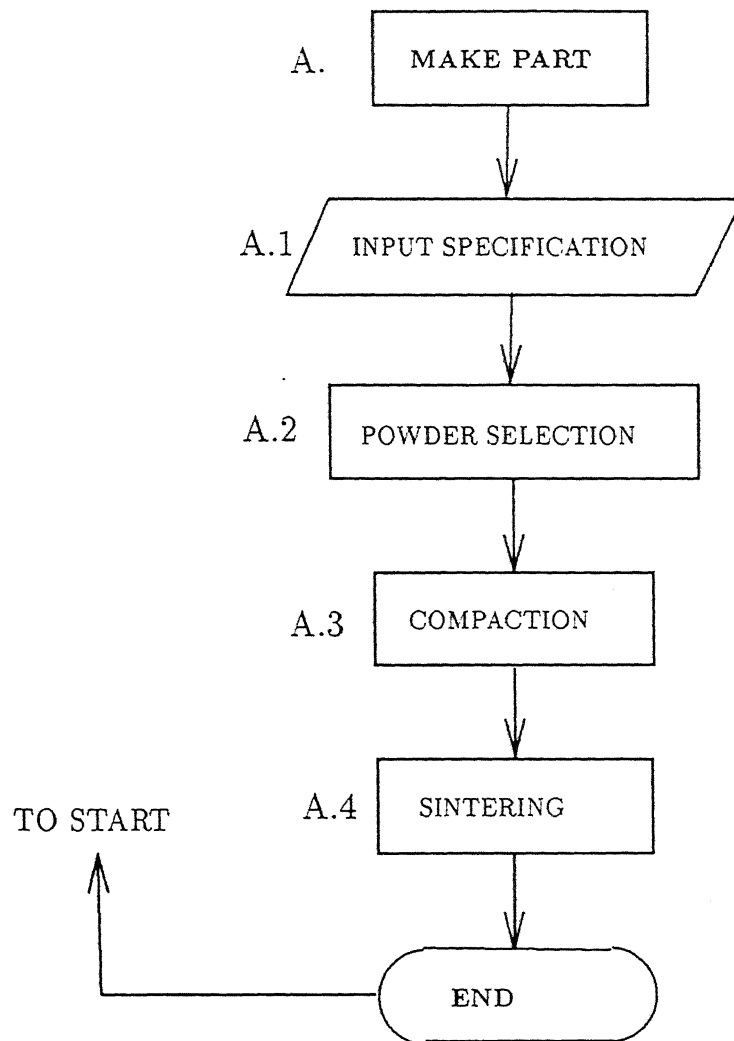
Figure 3.2: A top–down flow for the Make Part module.
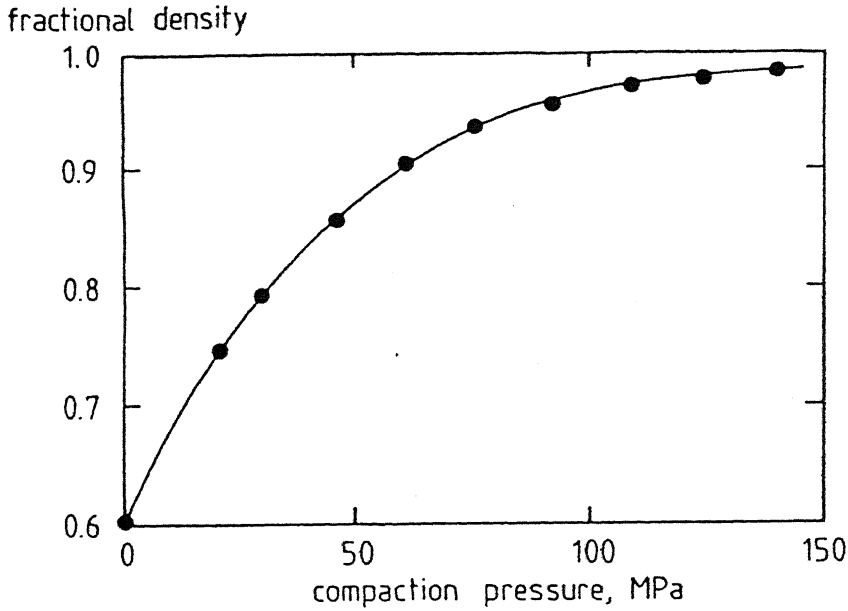
Figure 3.3: Fractional density vs. the compaction pressure.

Rearranging and integrating the above equation gives

$$\ln \left[\frac{(1-f)}{(1-f_o)} \right] = -KP \tag{3.2}$$

where,

f_o equals the fractional density without an applied pressure (also known as apparent density).

An alternative form suggested by *Heckel* incorporates a term A for initial rearrangement,

$$(1-f) = (1-f_o) \exp(-KP + A) \tag{3.3}$$

which is widely applied to powder compaction.

Equations 3.2 and 3.3 ignore the mechanism of compaction, yet they provide empirical starting points for many of the compaction models. There however exists numerous other models.

Although all models adequately predict a decrease in porosity with an increase in pressure, they often lack a physical basis. Generally the models oversimplify the

complexity of compaction. Inspite of the shortfallings, empirical equations that predict the density as a function of the compaction pressure are important in generalizing behaviour and comparing different particles. Probably the main problem is that compaction is not a simple combination of stages and mechanisms. Thus the mathematical treatments need to better reflect the complexity of the actual process.

3.1.2 Calculation of Load

The friction between the die wall and the powder causes a decrease in the pressure with depth in the particle bed. Particles under load exhibit a pseudo-fluid character that converts the uniaxial stress into radial stress. Consequently the redistribution in stress leads to a decrease in pressure with depth in a powder bed given by

$$P = P_o \exp(-4\mu zx/D_c) \qquad (3.4)$$

where,

P is the pressure at a point x below the top surface,

P_o is the applied pressure,

μ is the co-efficient of friction between the powder and the die wall,

z is the ratio of radial to axial stress and

D_c is the diameter of the compact.

Figure 3.4 shows the axial transmission of pressure in a cylindrical body under compaction. The difference in applied and transmitted pressure results from the frictional force at the die wall.

In this work the effect of friction is not considered. So the load is calaculated as

$$load = pressure \times cross\ sectional\ area$$

where,

pressure is the compaction pressure
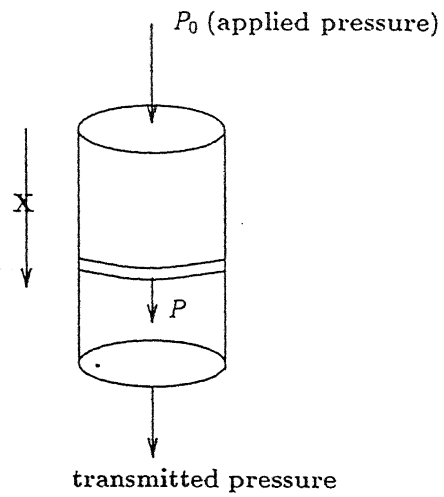
Figure 3.4: Axial transmission of pressure.
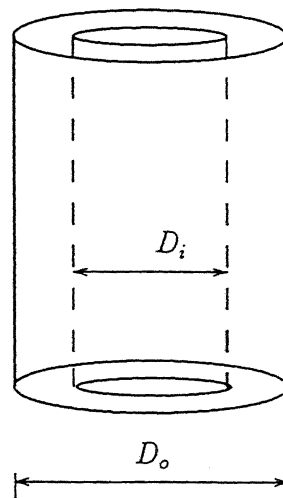
Figure 3.5: A hollow cylindrical part.

3.1.3   Calculation of Die Diameter and Core Rod Diameter

Let,

D_o = the outer diameter of the part to be made.

D_i = inner diameter of the part.

L = length of the part.

$K = \frac{D_i}{D_o}$ = ratio of inner diameter to outer diameter.

where $0.0 \leq K \leq 1.0$

M = mass of the part.

ρ_f = final density of the part after sintering.

ρ_p = density after compaction.

The volume of a hollow cylinder is given by :

$$V = \frac{\pi}{4}(D_o^2 - D_i^2)L$$

This can also be written as :

$$V = \frac{\pi}{4}(1 - K^2)D_o^2 L \tag{3.5}$$

for solid cylinder $K = 0$.

Elementary change in volume :

$$dV = \frac{\pi}{4}\left(1 - K^2\right)D_o^2\, dL + \frac{2\pi}{4}\left(1 - K^2\right)D_o\, L\, dD_o$$

Therefore volumetric strain,

$$\frac{dV}{V} = \frac{dL}{L} + 2\,\frac{dD_o}{D_o}$$

or

$$\epsilon_V = \epsilon_L + 2\,\epsilon_D \tag{3.6}$$

where,

ϵ_V = Volumetric strain.

ϵ_L = Axial strain.

ϵ_D = Radial strain.

During sintering both the diameter and the length of the compact changes. Assuming that,

$$\epsilon_L = \epsilon_D$$

we have,

$$\epsilon_V = 3\,\epsilon_L = 3\,\epsilon_D$$

Now,

Volume after compaction $= \frac{M}{\rho_p}$

Final volume of the part $= \frac{M}{\rho_f}$

change in volume (decrease) $= \frac{M}{\rho_p} - \frac{M}{\rho_f}$

Therefore volumetric strain,

$$\epsilon_V = \frac{dV}{V} = \frac{\frac{M}{\rho_p} - \frac{M}{\rho_f}}{\frac{M}{\rho_p}}$$

or,

$$\epsilon_V = 1 - \frac{\rho_p}{\rho_f} \qquad (3.7)$$

Thus,

$$\epsilon_L = \epsilon_D = \frac{1}{3}\,\epsilon_V = \frac{1}{3}\left(1 - \frac{\rho_p}{\rho_f}\right)$$

Let, dD_o be the change in outer diameter, dD_i the change in inner diameter and dL the change in compact length during sintering. Then,

$$\epsilon_D = \frac{dD_o}{D_o + dD_o}$$

and

$$\epsilon_L = \frac{dL}{L + dL}$$

From this dD_o and dL can be found out. Also we have,

$$dD_i = K\,dD_o$$

Therefore,

diameter of the die $= D_o + dD_o$

diameter of the core rod $= D_i + dD_i$

and, compact length $= L + dL$.

3.1.4   Press Selection

Tonnage and stroke are important considerations in selecting a pressing system. The tonnage capacity describes the maximum force the press will be capable of exerting during compression while maintaining acceptable life of the press components. stroke is usually given in terms of punch travel.

Tonnage Capacity

The total load requirement of a press is the product of the moulding pressure and the projected area of the part to be compacted.

$$Press \ load = Moulding \ pressure \ \times \ Projected \ area$$

Ejection Capacity

Ejection capacity is an important rating of a press usually stated as tons by the manufacturer of the press. Ejection load depends on punch, core rod and die side wall contact areas, tooling material, tool surface finish and amount and type of lubricants. Roughly ejection load is calculated by multiplying the part contact area with the tooling in the axial direction of pressing by the ejection breakaway pressure of the material.

The ejection breakaway pressure depends upon the amount of lubrication. With proper lubrication this can be reduced appreciably.
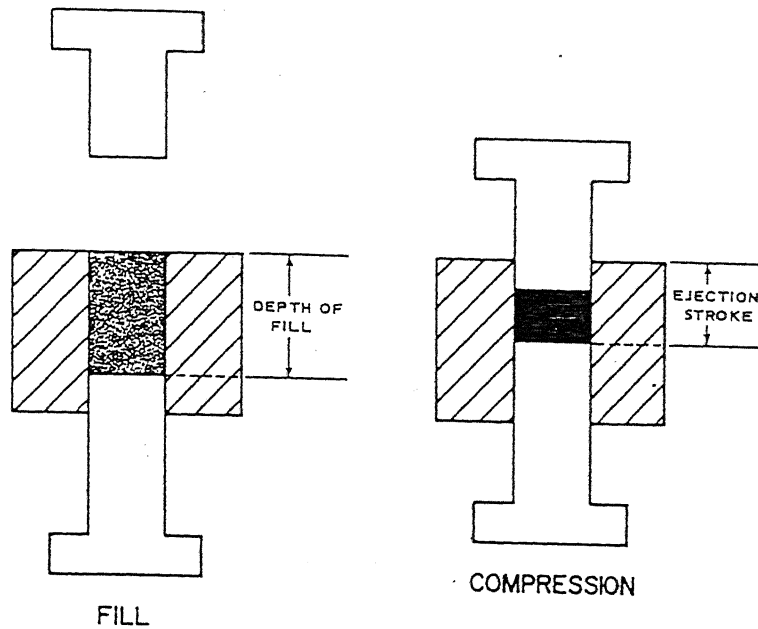
Figure 3.6: The die fill and ejection stroke

<u>Stroke Capacity</u>

The other consideration in selecting a press for a specific part is to determine if the press has sufficient die fill and ejection stroke. The depth of fill and the ejection stroke are shown in figure 3.6. The depth of fill can be calculated easily if the mass of the powder, its apparent density and the die diameter are known.

Since in the current work the frictional characteristic of the powder is not considered the selection of the press is done on the basis of its tonnage capacity with the assumption that it has sufficient ejection and stroke capacity.

3.2 Sintering

Sintering of powder compacts results in strengthening and usually also in densification of the powder mass. Sintering is a complex process during which several reactions take place.

An important stage in studying the mechanism of a complex physical process is the investigation of its kinetic characteristics by observing the changes with time of the parameters characterizing the development of the process.

The rate of specific reduction in the volume of pores after the volume has decreased to, v, is equal to :

$$\frac{dv}{d\tau \cdot v} = -q \left(\frac{v}{v_{in}}\right)^m \tag{3.8}$$

where,

v_{in} is the volume of pores at the time the isothermal process begins.

$q = \frac{dv}{d\tau} v_{in}$ is the rate of the specific reduction in the volume of pores at the isothermal starting point.

v is the porosity at any time,τ from the moment isothermal sintering begins.

and m is a constant.

It was found that in the absence of effects disrupting the densification process the relationship expressed in 3.8 holds for single phase bodies under practically any sintering conditions. The rate at which the densification rate decreases depends on the value of m.

Integration of equation 3.8 leads to an equation describing the change in volume of pores with time.

$$v = v_{in}(q\, m\, \tau + 1)^{-\frac{1}{m}} \tag{3.9}$$

where,

τ is the isothermal sintering time.

q is a co-efficient expressing the rate of reduction per unit volume of pores at $\tau = 0$.

and, m is a dimensionless constant.

The values of v and v_{in} can be expressed in any units including relative units. If the volume of pores in the compact, v_p, was used as the unit of measurement then $v = v_s/v_p$, at any time, τ and $v_{in} = v_s/v_p$ at $\tau = 0$.

Sintering time (in minutes)		Value of v_s/v_p
Total time	Isothermal Sintering time, τ	
8.0	0.0	0.892
22.0	14.0	0.850
38.0	30.0	0.833
90.0	82.0	0.816
128.0	120.0	0.810
240.0	232.0	0.799
360.0	352.0	0.787
480.0	472.0	0.780

Table 3.1: Variation of v_s/v_p with τ

The constants q and m can be found out from the experimental data of the pattern as shown in table 3.1[2] by using the method of selected points.

Other relations also exist. According to *Frenkel* :

$$v = v_{in} \left(1 - B\,\tau\right)^3$$

where,

τ represents the time and B is a constant.

It follows from this relation that after sintering for the time $\tau = 1/B$ the pores should disappear which however does not happen.

The equations discussed above gives only a time dependence of pores at a particular temperature.

The variation of the change in volume of pores during sintering with both time and temperature is given by

$$\ln\left(\frac{v}{v_{in}}\right) = -\frac{b}{a}\exp\left(-\frac{\Delta E}{RT}\right)\ln[aN_{in}\exp\left(-\frac{E_a}{RT}\right)\tau + 1] \qquad (3.10)$$

---

[2]Taken from *Densification of Metal Powders during Sintering*, Ivensen,V.A., page–28.

where,

v = relative volume of pores expressed as v_s/v_p.

v_{in} = relative volume of pores at the beginning of isothermal sintering.

v_p = volume of poers in compact before sintering.

v_s = volume of pores after sintering.

aN_{in} = the relative concentration (or Kinetic characteristic of concentration) of defects at the time isothermal sintering actually begins (in hr^{-1}).

E_a = the activation energy of elimination of defects (cal/gm – atom).

E_b = the activation energy of flow associated with lattice defects (cal/gm – atom).

T = Absolute sintering temperature ($^{\circ}K$).

R = Gas constant.

τ = isothermal sintering time (hr).

3.2.1   Determination of Activation Energy

The value of activation energy of flow, E_b, can be found by determining the rates of reduction in volume of pores before and after rapid change of the temperature following a more or less long period of isothermal sintering. If the change from one sintering temperature to another is rapid then the concentration of defects does not have time to change substantially. In this case the change in the rate depends mainly on the activation energy of the bulk flow.

The activation energy can be determined by using the standard formula :

$$E_b = R\ \frac{\ln \dot{v}_2 - \ln \dot{v}_1}{\frac{1}{T_1} - \frac{1}{T_2}} \qquad . \qquad (3.11)$$

where,

$\dot{v} = \frac{dv}{d\tau} \cdot \frac{1}{v}$.

Data can be of the type as shown in the table[3] 3.2.

---

[3]Takenfrom *Densification of Metal Powders during Sintering*, Ivensen,V.A., page—139.

Powder	Temperature of first sintering period, (^{0}C)	$\dot{v}_1$ at end of first period (h^{-1})	Temperature of second sintering period, (^{0}C)	$\dot{v}_2$ at end of second period (h^{-1})
Copper	850.0	0.0320	1000.0	0.881
Nickel	850.0	0.0258	1000.0	3.95
Silver	740.0	0.0185	850.0	1.54

Table 3.2: Experimental data obtained with a stepped rise in temperature to calculate E_b.

The activation energy of another phenomenological elementary process — the elimination of defects, can be determined from experimental data characterizing the temperature dependence of m in 3.9. Using the value of m at two temperatures we find the value of ΔE by means of equation 3.12. Then subtracting ΔE from E_b, we find E_a.

$$\Delta E = R \, \frac{\ln(m_1) - \ln(m_2)}{\frac{1}{T_1} - \frac{1}{T_2}} \tag{3.12}$$

$$E_a = E_b - \Delta E$$

and,

$$\frac{a}{b} = m_{1(2)} \, \exp\left(-\frac{\Delta E}{R \, T_{1(2)}}\right) \tag{3.13}$$

More precise values of ΔE and a/b can be found by plotting $\log m$ vs. $1/T$. Since the relationship is linear, a straight line can be found along the experimental points. On the straight line two points are selected with co-ordinates $\log m_1$, $1/T_1$ and $\log m_2$, $1/T_2$.

The constants E_a, E_b and a/b are constants of the powder. Some complication is introduced by the fact that aN_{in} enters into equation 3.10 which is not a constant

of the powder. The concentration of defects at the beginning of isothermal sintering depends on the heating period and also the temperature range of heating to the beginning of isothermal sintering. The value of aN_{in} therefore must conform with the given conditions at the beginning of isothermal sintering. To calculate aN_{in} it is necessary to know constants q and m in equation 3.9. If they are found from three selected points on the sintering curve of v_s/v_p vs. τ then

$$aN_{in} = q\,m\,\exp\left(\frac{E_a}{R\,T}\right)$$

Also,

$$aN_{in} = \frac{\left(\frac{v_{in}}{v_1}\right)^m - 1}{\tau_1}\,\exp\left(\frac{E_a}{R\,T}\right) \tag{3.14}$$

With the above constants known the course of densification can be calculated.

3.2.2   Total Densification

Densification during isothermal sintering constitutes only part of the total densification attained in sintering. A substantial portion of the total densification occurs in the period of rising temperature. The rate of reduction in volume of pores at the beginning of isothermal sintering and the general course of subsequent densification depends not only on the temperature but also to a considerable extent on the conditions of heating to isothermal sintering temperature.

Assuming a constant rate of increase in temperature, the actual heating graph may be of the type shown in figure 3.7. But for ease in calculation we may use the idealized heating graph of the sintered body containing two straight lines, one sloped and one horizontal as shown in figure 3.7.

Under actual sintering conditions such heating is impossible to accomplish, since an instantaneous change from rising temperature to isothermal holding is impossible.

The condition of the sintered body, its capacity for further densification depends mainly on the value of aN, the kinetic characteristic of the concentration of defects.
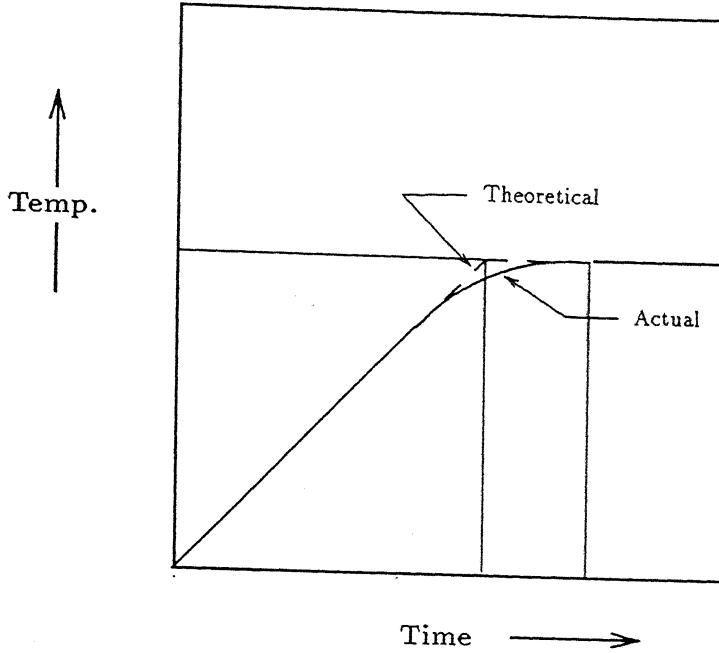
Figure 3.7: Initial heating to isothermal sintering temperature

With heating at a constant rate of increase in temperature the variation of aN with the temperature reached and the heating rate is expressed by the equation :

$$aN = \frac{aN_0}{\left[\frac{aN_0}{\alpha} \int_{T_0}^{T} \exp\left(-\frac{E_a}{RT}\right) dT\right] + 1} \qquad (3.15)$$

where,

aN_0 is the kinetic characteristic of the concentration of defects in the original powder.

α is the rate of increase of temperature in($^\circ K/hr$)

and T_0 is the temperature before heating begins.

The value of the integral,

$$\int_{T_0}^{T} \exp\left(-\frac{E_a}{RT}\right) dT$$

is calculated by numerical integration. For practical purposes it is convenient to use

tabular numerical values of the integral as shown in table 3.3[4].

Temperature, °C	log F_T for E_a (cal/g-atom)									
	10,000	20,000	30,000	40,000	50,000	60,000	70,000	80,000	90,000	100,000
500	−0.884	−3.894	−6.874	−9.823	−12.745	−15.648	−18.540	−21.422	−24.298	−27.168
550	−0.654	−3.494	−6.304	−9.082	−11.832	−14.564	−17.284	−19.995	−22.699	−25.398
600	−0.467	−3.147	−5.797	−8.423	−11.021	−13.601	−16.169	−18.728	−21.280	−23.827
650	−0.272	−2.822	−5.342	−7.833	−10.296	−12.740	−15.173	−17.596	−21.280	−23.827
700	−0.101	−2.531	−4.931	−7.301	−9.642	−11.965	−15.173	−17.596	−20.013	−22.424
750	+0.050	−2.270	−4.560	−6.819	−9.050	−11.263	−14.276	−16.578	−18.873	−21.163
800	+0.191	−2.029	−4.219	−6.379	−8.511	−11.263	−13.464	−15.657	−17.842	−20.022
850	+0.323	−1.807	−3.907	−5.977	−8.019	−10.625	−12.727	−14.820	−16.906	−18.986
900	+0.422	−1.618	−3.628	−5.608	−7.566	−10.042	−12.053	−14.055	−16.051	−18.041
950	+0.553	−1.417	−3.357	−5.267	−7.150	−9.507	−11.435	−13.355	−15.267	−17.174
1000	+0.658	−1.242	−3.112	−4.952	−6.764	−9.014	−10.866	−12.709	−14.546	−16.377
1050	+0.771	−1.069	−2.879	−4.659	−6.407	−8.559	−10.341	−12.114	−13.880	−15.641
1100	+0.863	−0.917	−2.667	−4.387	−6.074	−8.136	−9.853	−11.562	−13.263	−14.959
1150	+0.906	−0.803	−2.475	−4.132	−5.764	−7.744	−9.401	−11.049	−12.690	−14.326
1200	+0.985	−0.658	−2.286	−3.890	−5.473	−7.377	−8.978	−10.571	−12.156	−13.736
1250	+1.059	−0.537	−2.117	−3.669	−5.201	−7.034	−8.584	−10.124	−11.657	−13.185
1300	+1.128	−0.447	−1.953	−3.461	−4.945	−6.713	−8.214	−9.706	−11.190	−12.670
1350	+1.194	−0.317	−1.799	−3.264	−4.704	−6.412	−7.867	−9.313	−10.752	−12.186
1400	+1.256	−0.202	−1.642	−3.068	−4.476	−6.128	−7.540	−8.944	−10.340	−11.731
1450	+1.315	−0.102	−1.500	−2.893	−4.262	−5.861	−7.233	−8.596	−9.952	−11.303
1500	+1.372	−0.008	−1.374	−2.727	−4.058	−5.608	−6.942	−8.267	−9.586	−10.898
						−5.368	−6.667	−7.956	−9.239	−10.516

Table 3.3: Values of $\log(F_T)$.

$$\int_{T_0}^{T} \exp\left(-\frac{E_a}{RT}\right)\, dT \;=\; \int_{0}^{T} \exp\left(-\frac{E_a}{RT}\right)\, dT \;-\; \int_{0}^{T_0} \exp\left(-\frac{E_a}{RT}\right)\, dT$$

$$=\; F_T \;-\; F_{T_0}$$

$$\approx\; F_T$$

Since F_T is many orders larger than F_{T_0}, the latter function can be neglected.

For comparison with the table it is convenient to use values of $\log F_T$. The values of $\log F_T$ for intermediate values of E_a and temperature are found by proportional interpolation.

If $E_{a(L)}$ and $E_{a(U)}$ are values closest to the given value of E_a with $E_{a(U)} > E_a > E_{a(L)}$ and $\log F_{T(U)}$, $\log F_T$, $\log F_{T(L)}$ are the corresponding values of

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[4]Taken from *Densification of Metal Powders during Sintering*, Ivensen,V.A., page–170

the logarithms of the function F_T, then

$$\log F_T = \log F_{T(L)} + \frac{\left(\log F_{T(U)} - \log F_{T(L)}\right)}{\left(E_{a(U)} - E_{a(L)}\right)} \times \left(E_a - E_{a(L)}\right)$$

From the logarithm we find F_T the value of which is used to determine aN_{in} by :

$$aN_{in} = \frac{aN_0}{1 + \frac{aN_0}{\alpha F_T}} \tag{3.16}$$

Thus aN_{in} can be calculated for given conditions of the beginning of isothermal sintering if the value of aN_0 is known.

What remains now is to find the porosity level at the point when isothermal sintering just begins. With the heating rate assumed to be uniform to the isothermal sintering temperature and idealized heating graph marked by two straight lines as shown previously in figure 3.7 the change in porosity in the pre-isothermal sintering stage may follow the pattern :

$$\frac{v_s}{v_p} = \exp(-\alpha \tau c) \tag{3.17}$$

where,

α = heating rate in $(^\circ K/hr)$.

τ = time of heating (hr).

c = a constant of the powder.

At the isothermal point, $v_s = v_{in}$ and $\tau = \tau_{in}$. Hence,

$$\frac{v_{in}}{v_p} = \exp(-\alpha \tau_{in} c) \tag{3.18}$$

3.3   Density Strength Relationship

Many models have been developed to describe the tensile behaviour of sintered materials. One of the simple model of them is the *Brick Model*[5].
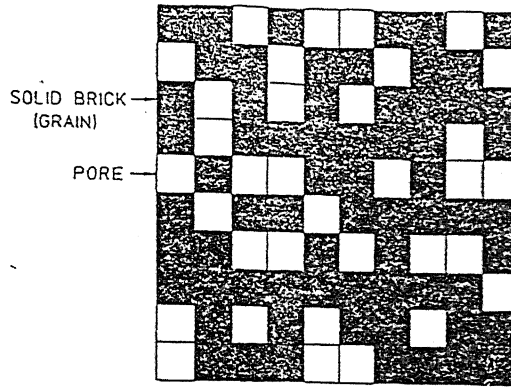
Figure 3.8: Typical section of a Simple brick model.

3.3.1   Brick Model

The pores and particles may alternatively be modelled as a layered randomly organized array of cubes. Particles are represented by solid cubes and pores by cubic spaces. Figure 3.8[6] shows an approximation of the cross section of a porous material. The stress concentrating effects due to pore geometry are ignored.

The strength, $(\sigma_{UTS})_\rho$ of the sintered material is proportional to $\left(1 - P^{\frac{2}{3}}\right)^2$ and it may be written as

$$\frac{(\sigma_{UTS})_\rho}{(\sigma_{UTS})_{\rho_0}} = \left(1 - P^{\frac{2}{3}}\right)^2 \qquad (3.19)$$

where,

$(\sigma_{UTS})_\rho$ is the Ultimate tensile strength of the material at density ρ.

$(\sigma_{UTS})_{\rho_0}$ is the Ultimate tensile strength of the material at density ρ_0.

P is the fractional porosity given by :

$$P = \frac{\rho_0 - \rho}{\rho_0}$$

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[5]Due to *Fleck* and *Smith*

[6]Taken from the paper of *Fleck* and *Smith*.
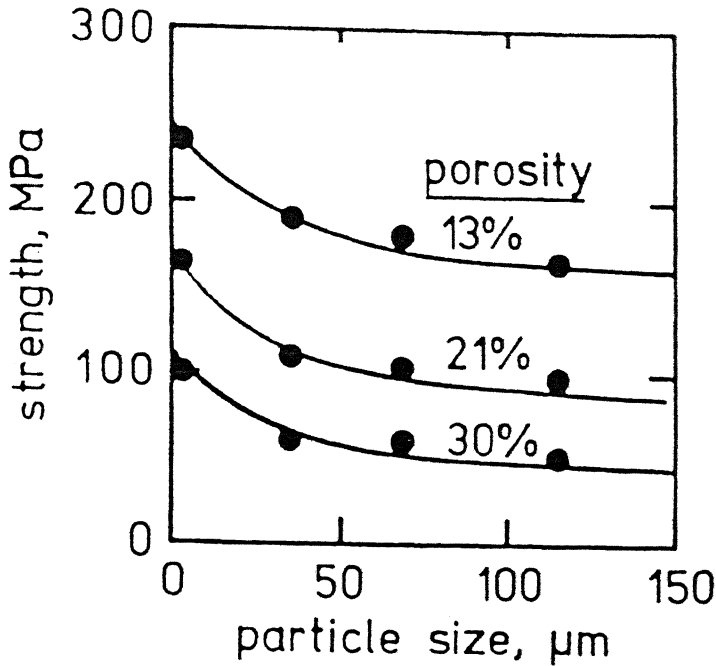
Figure 3.9: Tensile strength dependence on particle size.

The ultimate tensile strength value of a material is a function of several factors. One of the important of them is the grain size of the powder as figure 3.9 shows. The above model does not relate strength to the grain size. It may be written as :

$$\frac{(\sigma_{UTS})_\rho}{(\sigma_{UTS})_{\rho 0}} = K \left(1 - P^{\frac{2}{3}}\right)^2 \tag{3.20}$$

where,

K whose value lies between 0 and 1 may be assumed to be a function of grain size.

From figure 3.9[7] it can be inferred that the shape of the curve of K vs. grain size will be similar to the curve of strength vs. grain size. Furthermore it may be noticed that the curves are exponential in nature. Accordingly it may be written as :

$$K = B + (1 - B) \exp(- A X) \tag{3.21}$$

[7]Taken from *Powder Metallurgy Science*, R.M.German, page–241

where,

B is a constant whose value lies between 0 and 1.

A is also a constant and positive.

X is the grain size in micrometer (μm)

For certain range of porosity A and B may be assumed to be constants of the powder. Solving equation 3.21 numerically for two sets of values of K and X the constants A and B may be obtained.

3.4   Optmization

As has been seen earlier there are three parameters involved in the sintering process — sintering temperature, sintering time and heating rate. Various combinations of these parameters may lead to a common goal. A stratregy will have to be found out to select one of them – optimization. The basis of optimization here is to find out the total heat spent in the process of sintering.

The heating has two parts :

1. The rise in temperature (initial heating).

2. Heating at constant isothermal sintering temperature.

1. The initial heating consists of two parts.

   (a) Heat that goes inside the compact to raise it's temperature.

   (b) Heat that is dissipated due to difference in temperature of the compact being heated and the ambient temperature.

1. (a) If we assume that the thermal capacity of the compact does not change with temperature then

$$heat\ absorbed = \gamma \times (T_s - T_0) \qquad (3.22)$$
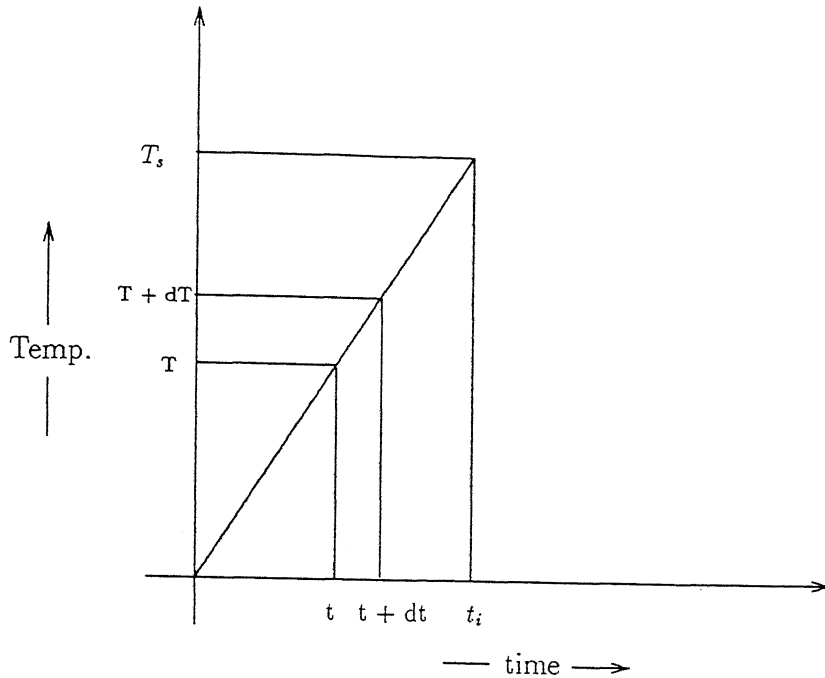
Figure 3.10: Uniform temperature rise to sintering temperature.

where,

T_s = sintering temperature.

T_0 = ambient temperature.

γ = is the thermal capacity.

(b) Let dQ be the heat dissipated in time dt when the temperature rises from T to $T + dT$. Therefore :

$$dQ = H_d \, (T - T_0) \, dt \qquad (3.23)$$

where,

H_d = heat dissipation constant.

It is assumed that H_d does not change with temperature.

Now, $T = T_0 + \alpha \, t$

where,

α = heating rate. and

$t =$ time.

Thus from equation 3.23

$$dQ = H_d \left(T_0 + \alpha\, t - T_0\right)\, dt$$

$$= H_d\, \alpha\, t\, dt$$

Integrating within proper limits,

$$Q = H_d\, \alpha \int_0^{t_i} t\, dt$$

where,

$t_i =$ is the time to reach the isothermal sintering temperature. Thus,

$$Q = H_d\, \alpha\, \frac{t_i^2}{2} \qquad (3.24)$$

2. Let T_s be the sintering temperature and T_0 the ambient temperature.
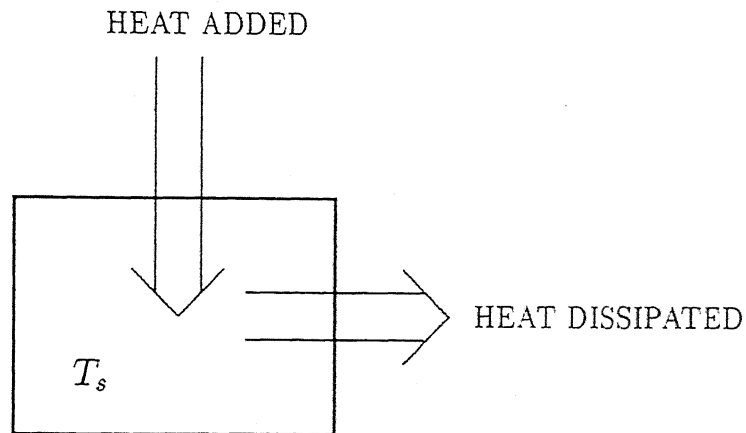
HEAT ADDED

Figure 3.11: Equilibrium

At equilibrium,

$$Rate\ of\ heat\ supplied\ =\ Rate\ of\ heat\ dissipated$$

$$Rate\ of\ heat\ dissipation\ =\ H_d\left(T_s - T_0\right)$$

where, H_d is the heat dissipation constant.

Therefore,

$$Heat\ added\ =\ Heat\ dissipated$$
$$=\ H_d\ (T_s - T_0)\ t_s \qquad (3.25)$$

where, t_s is the isothermal sintering time.

Summing up equations 3.22, 3.24 and 3.25 the total heat added :

$$Q_{total} = \gamma\ (T_s - T_0) + H_d\ \alpha\ \frac{t_i^2}{2} + H_d\ (T_s - T_0)\ t_s \qquad (3.26)$$

Assuming that the 1'st term in the right hand side of equation 3.26 is smaller compared to the other two terms,

$$Q_{total} = H_d\ \alpha\ \frac{t_i^2}{2} + H_d\ (T_s - T_0)\ t_s$$

Now,

$$t_i = \frac{T_s - T_0}{\alpha}$$

Thus,

$$Q_{total} = H_d\ \left[\frac{(T_s - T_0)^2}{2\alpha} + (T_s - T_0)\ t_s\right]$$

Hence the *objective function* is :

$$\psi = \frac{(T_s - T_0)^2}{2\ \alpha} + (T_s - T_0)\ t_s \qquad (3.27)$$

Chapter 4

Implementation

The system is implemented on the HP Graphics Work station, operating on the Unix environment and is coded in C. The reason for using the language C is its well organised data structures and the dynamic memory allocation facility thereby costing only the required amount in terms of memory.

The system is designed to be totally interactive and user friendly. It recieves inputs from the user in the form of menu options.

The next few sections describe how the various elements of the system work in tandem toward a common objective.

4.1 Shapes Covered

The shapes covered in the current model are :

- Cylindrical :

    1. Solid Cylinder.

    2. Hollow Cylinder.

4.2   Input to the System

The inputs to the system are :

1. Part geometry :

    (a) For solid cylinder : part diameter and part length.

    (b) For hollow cylinder : outer diameter, inner diameter and part length.

2. Property : required ultimate tensile strength of the part.

4.3   Powder Selection

After the input part specification, the first task is to select a powder that may make the part. The flow chart of this is shown in figure 4.1.

After the powders are read from the powder data base, it is to be found out whether a powder can make the part or not. Using equation 3.20 the relative density required to obtain the desired strength is found out. The relative density is defined as the ratio of any density of the material to the density of the material in the wrought state. A powder can make the part if its required relative density lies between *apparent relative density* and 1.0.

If none of the powders are able to make the powder then either a new powder is to be read or the part has to be cancelled. If the user wants to input a new powder then after inputting the powder the condition is again checked whether the part can be made or not.

Powders whose required relative density lies in the range of *apparent relative density* and 1.0 become a candidate for powder selection. A list of all such candidate powders is made with decreasing order of required relative density which also represents a decreasing order of preferences with the assumption that higher the relative density lower will be the voids and better will be its other properties.
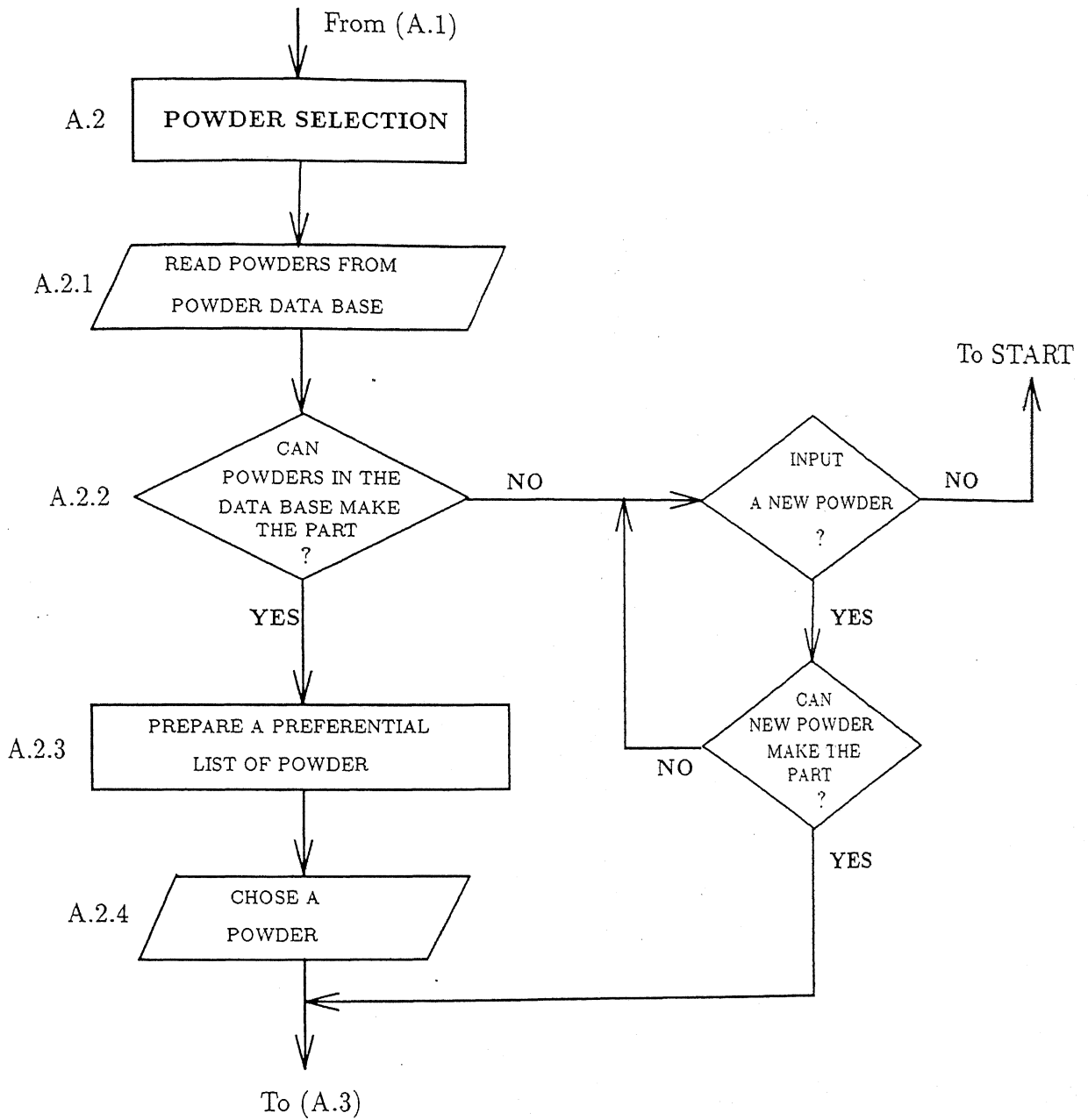
Figure 4.1: A top-down pull–out for powder selection module.

The final selection of the powder is done by the user from among the candidate powders.

4.4 Compaction

The compaction module is concerned with the selection of pressure and press. The flow chart of the compaction module is shown in figure 4.2.

From (A.2)

A.3 ┌─────────────┐
     │ COMPACTION │
     └─────────────┘

A.3.1 ┌─────────────┐
       │ PRESSURE   │
       │ SELECTION │
       └─────────────┘

A.3.2 ┌─────────────┐
       │   PRESS   │
       │ SELECTION │
       └─────────────┘

To (A.4)

Figure 4.2: Flow within the compaction module.

4.4.1 Selection of Pressure

Various steps of this module is shown in figure 4.3.

The graph of relative density vs. pressure is shown in figure 4.4. The density rise is significant in the initial stages and after some increase in pressure the density
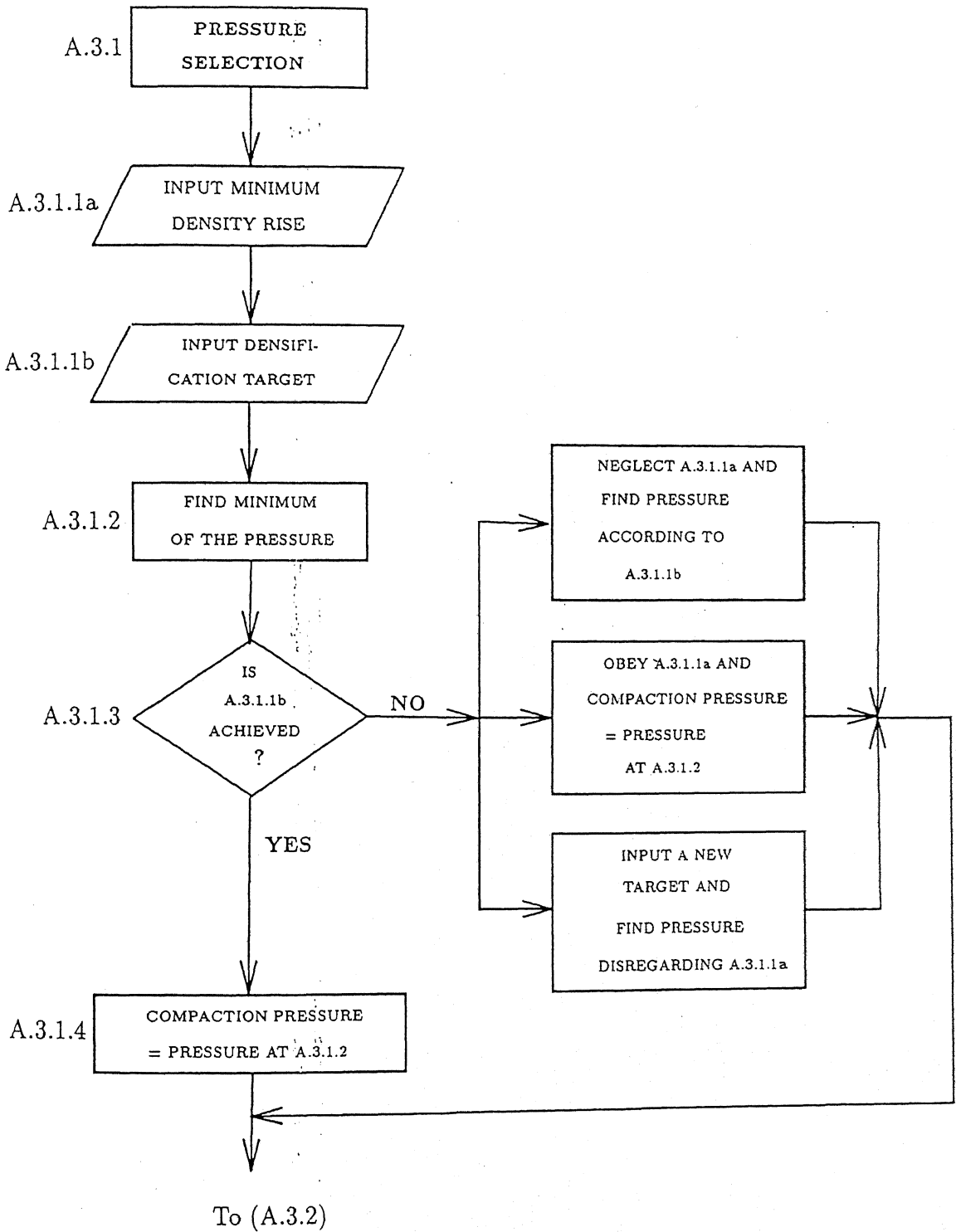
Figure 4.3: Flow chart for Pressure Selection.
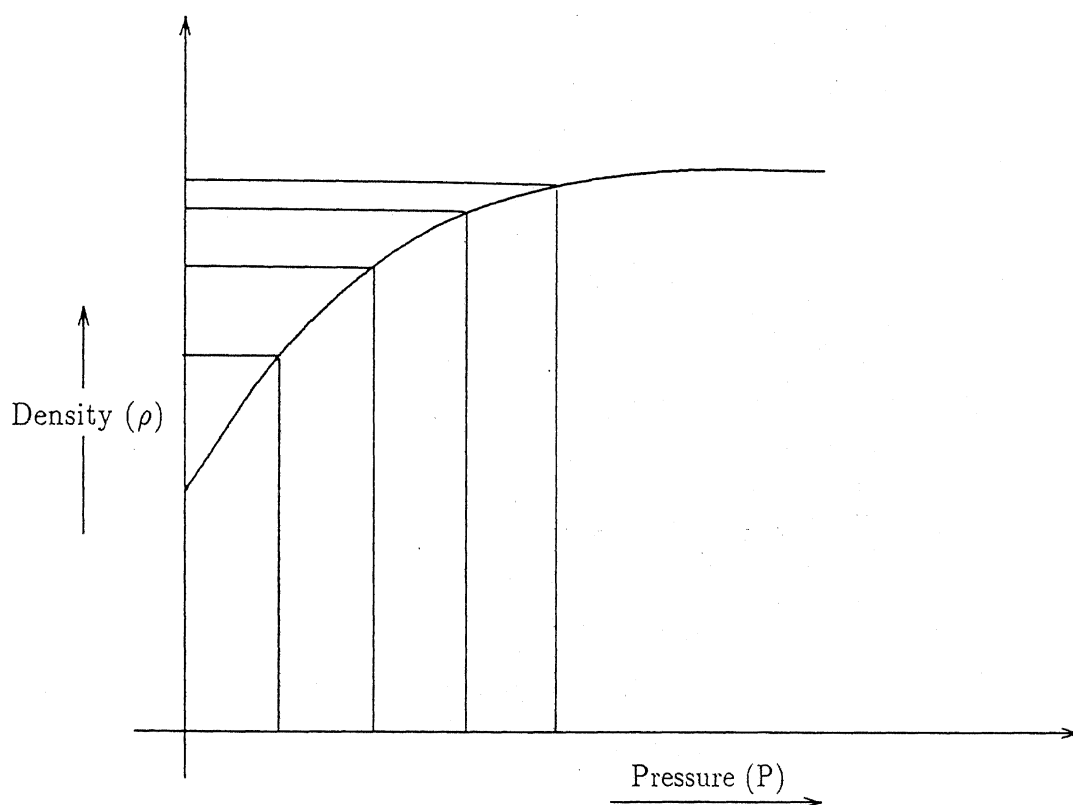
Figure 4.4: Relative density vs. pressure graph.

improvement is only marginal. So there is no point compacting beyond certain pressure as the outcome in terms of density improvement is not justifiable to the cost of increasing pressure.

So what is done is that for each unit rise in pressure the increase in density is noted down. The density increase is greater at earlier stages and gradually decreases. The process is stopped when the density increase is less than a minimum rise in density per unit pressure rise specified earlier. The minimum density rise per unit of pressure is to be supplied in terms of percentage.

In addition to this there is also a controlling factor to guide the selection of pressure – the percentage densification target. The percentage densification is defined as :

$$percentage\ densification\ =\ \frac{density\ after\ compaction - apparent\ density}{final\ density - apparent\ density} \times 100.0$$

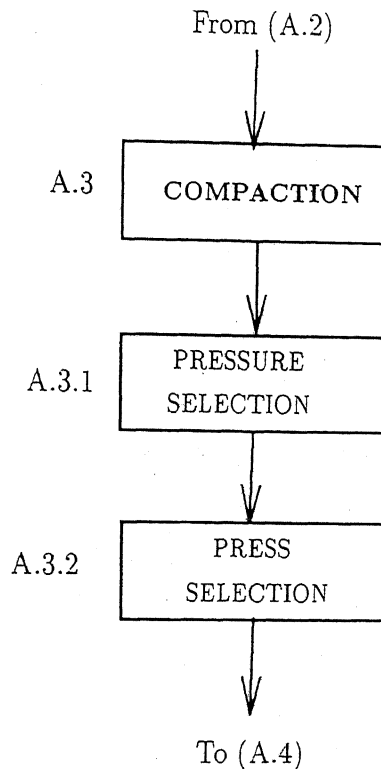The above two controlling factors will yield different pressure values. The minimum of them is considered. If the percentage densification target is reached without violating the minimum density rise criterion then the pressure is selected. If however due to minimum density rise criterion the densification target is not achieved then the user is to select one out of the following three options :

1. Ignore minimum density rise criteria and select pressure as the pressure required to achieve the densification target.

2. Obey the minimum density rise criteria and pressure selected is the minimum pressure as considered above.

3. Input a new densification target and select the pressure to achieve the target disregarding the minimum density rise criteria.

After the pressure is selected the relative density after compaction is found out using equation 3.3 and

$$relative\ density = 1.0 - porosity$$

4.4.2   Selection of Press

Various steps of this module is shown in figure 4.5.

The diameter of the die (and core rod for hollow part) is found out as described in section 3.1.3.

The fill length can be found out by dividing the volume of the powder to be taken, by the cross sectional area during compaction. The load on the press is found out by multiplying the compaction pressure and the cross sectional area.

The data base for press contains the capacity of the presses. Presses are selected on the basis of their capacity. The press capacity should be atleast 1.5 times the load required. If the presses in the database do not have sufficient capacity then no press is selected; however the process continues. A list of all the candidate presses is prepared with increasing order of capacity which also represents the decreasing order of preference.

The final selection of the press is done by the user.

The part then proceeds for sintering.

4.5   Sintering

The working of the current module can best be described with the help of the flowchart 4.6.

Normally the maximum sintering temperature is 95.0% of the melting point of the material. But the user can give any value not exceeding the melting point of the material.

The initial heating rate is assumed to be linear. The heating rate influences the sintering behaviour. The heating rates available will have to be mentioned *i.e.* the lowest and highest heating rates.

The maximum acceptable sintering time will have to be provided which specifies a domain within which solution is to be found out.

FROM A.3.1

A.3.2.1	FIND OUT DIE DIA AND CORE DIA
A.3.2.2	FIND OUT THE LOAD REQUIRED
A.3.2.3	READ PRESSES FROM PRESS DATA BASE

A.3.2.4 — IS PRESS CAPACITY SUFFICIENT ? — NO

YES

| A.3.2.5 | PREFERENTIAL LIST OF PRESSES |

A.3.2.6 — CHOSE A PRESS

TO SINTERING

Figure 4.5: Flow chart for Press Selection.

From COMPACTION

A.4 SINTERING

A.4.1 READ SINTERING LIMITS
(TEMPERATURE, TIME)

REINPUT
SINTERING LIMITS

A.4.2 IS THERE ANY SOLUTION ?

NO

START FROM
COMPACTION

To A.3

FORGET
THE PART

To START

YES

A.4.3 PREFERENTIAL LIST OF
ACCEPTABLE CASES

A.4.4 CHOSE A CASE

A.4.5 APPEND THE PART TO
THE LIST OF PARTS MADE
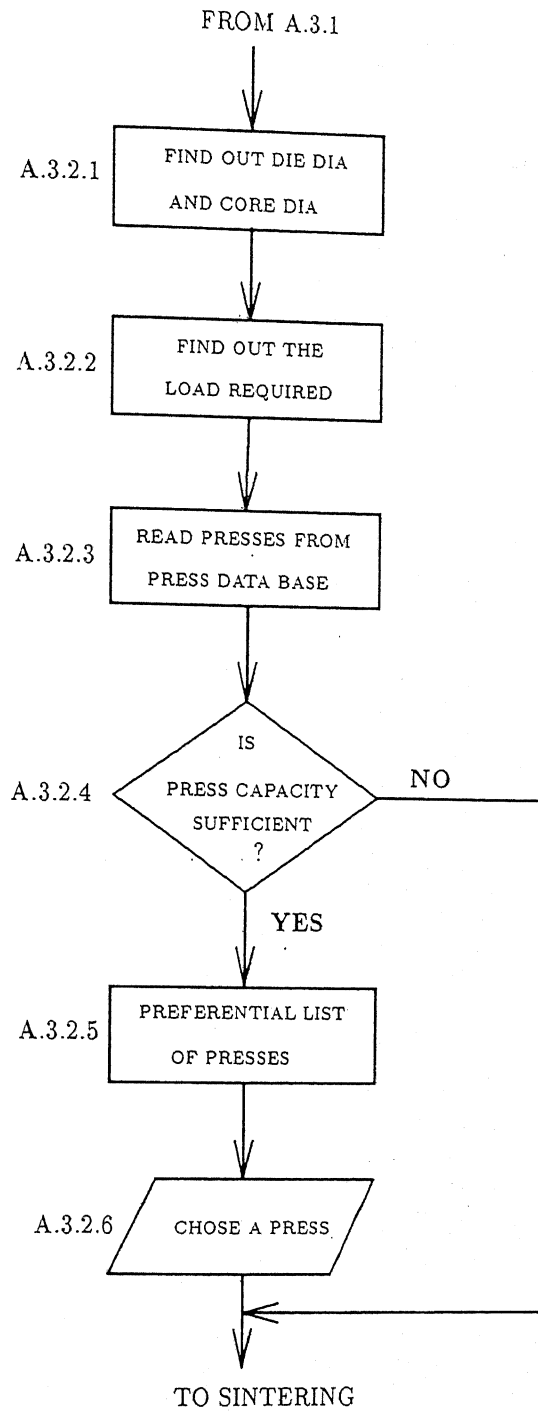
To START
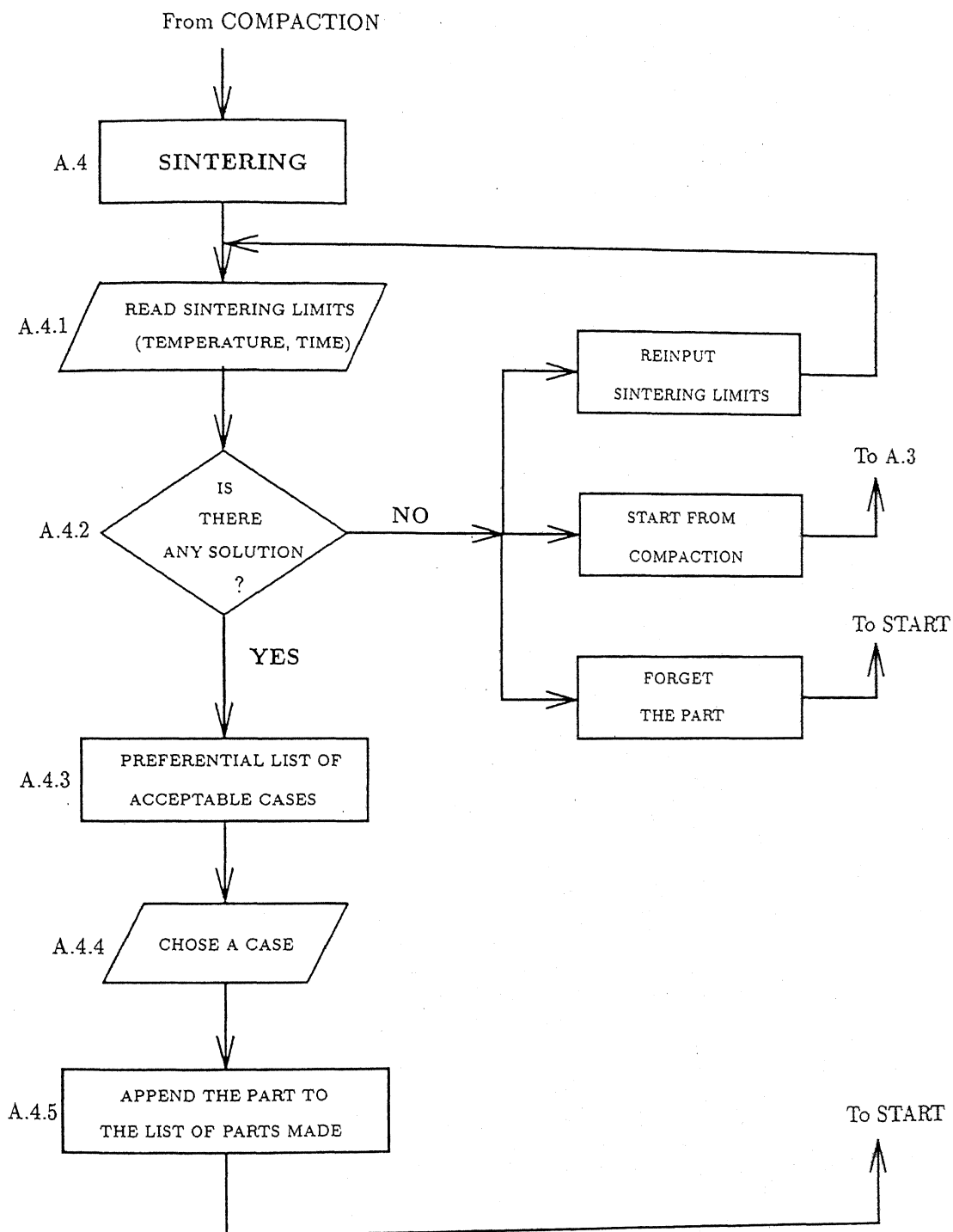
Figure 4.6: A top down flow for the sintering module.

The values of the above three variables — maximum sintering temperature, lowest and highest heating rates and the maximum acceptable sintering time — form the confining boundaries of the solution space.

For certain sintering temperature and heating rates sintering time is found out using equation 3.10. The values of sintering time for various combinations of sintering temperature and heating rate are found out. If none of the sintering times is below the maximum acceptable sintering time as specified earlier then the user have three choices :

1. Reinput the sintering limits – By increasing the maximum acceptable sintering time perhaps a solution may be found out.

2. Start from compaction – If more densification is achieved during compaction a solution may be found out.

3. Forget the part and start afresh with a new part.

There can be many solutions in the above defined solution space all of which are acceptable. There must be some methodology to select one of them. The methodologies can be many and the one which can be applied depends much on the actual production conditions. The condition which involves least total heat as calculated in section 3.4 is assumed to be the best condition here.

A list of all the acceptable cases is prepared with decreasing order of preference. The final selection of a particular case is done by the user.

After the part has been successfully made it is appended to the list of parts made.

4.6   Data Addition

The scope of the system is limited by the existing database stored in the form of data files. It is expected that the system will perform better if its database can

be expanded. Provision is kept so that the databases can be expanded through the program. So the databases are essentially dynamic databases.

The flow chart for data addition module is shown in figure 4.7.

The range of temperature and E_a, the activation energy of elimination of defects for which calculations of sintering can be done is dictated by table 3.3 which is used for calculating the integral as described in section 3.2.2.

The melting point of the new powder is read. If its melting point is less than the minimum temperature in the integral table the powder is cancelled and the user is asked to select one of the following two :

1. Input another powder.

2. Quit data addition module.

After inputting the activation energies, E_a is found out. If E_a for the powder lies outside the E_a range in the integral table the powder is cancelled and user is asked to select one of the following two options :

1. Input another powder.

2. Quit data addition module.

Then other quantities are read one by one.

The reading of values for E_b, ΔE, a/b and *isotherm constant* have the submenus of their own in that user may directly supply their values or can calculate their values. Finally the powder is appended to the existing powder data base.

4.7   Output

After the part has been made there is also an option for graphic display which is a very crude simulation of the compaction and sintering process. It shows dimensions of the part at various stages of the process. A densification curve can also be requested

From START

B. DATA ADDITION

B.1 INPUT MELTING POINT

B.2 IS M.P. < MIn. TEMP. IN INTEGRAL TABLE ?

YES → CANCEL POWDER → INPUT ANOTHER POWDER

BACK TO ROOT MENU → TO START

NO

B.3 INPUT ACTIVATION ENERGIES

B.4 DOES E_a LIE BETWEEN MAX. AND MIN. IN THE INTEGRAL TABLE ?

NO → CANCEL POWDER → INPUT ANOTHER POWDER

BACK TO ROOT MENU → TO START

YES

B.5 INPUT OTHER QUANTITIES

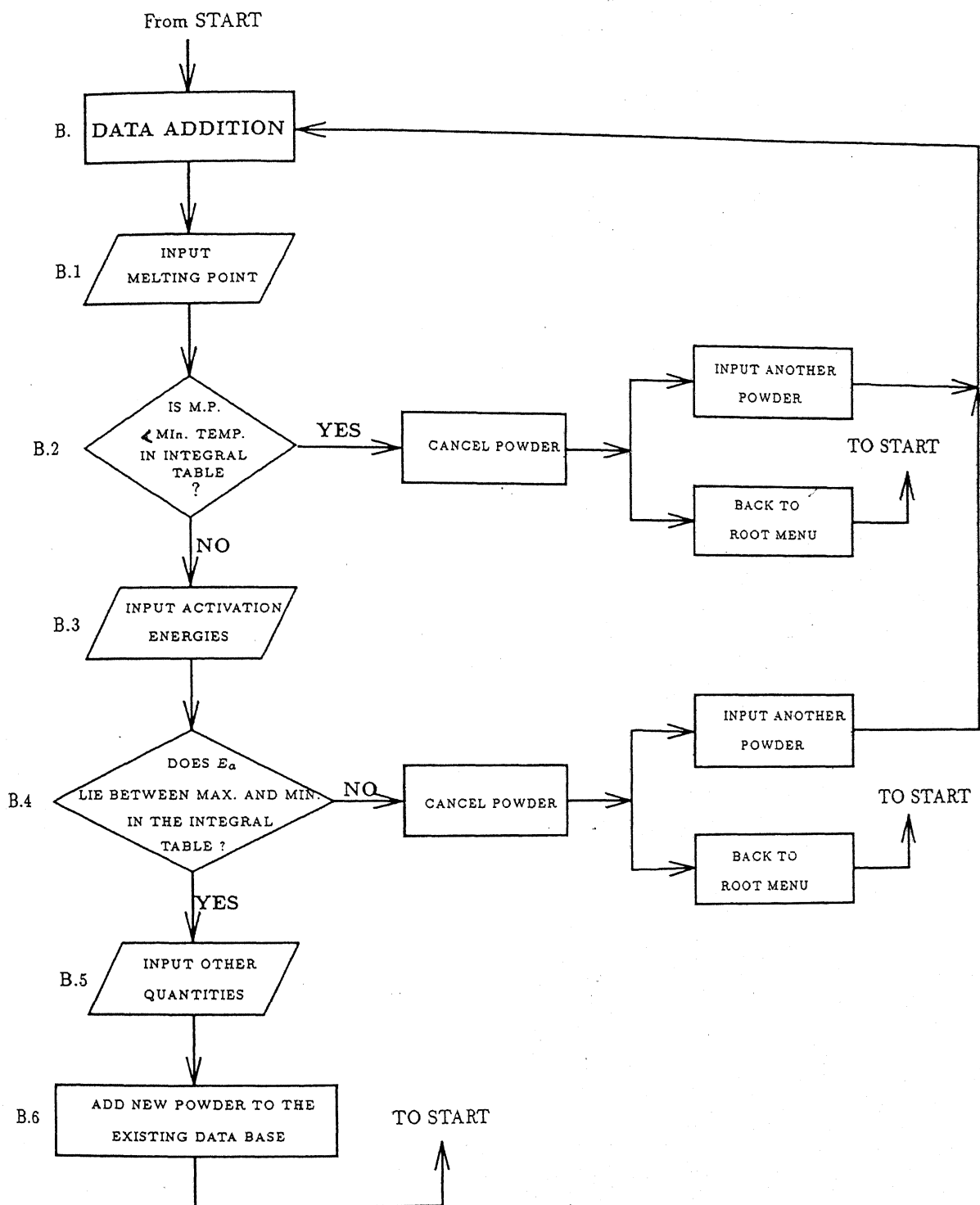B.6 ADD NEW POWDER TO THE EXISTING DATA BASE → TO START

Figure 4.7: various stages in the data addition module.

to which shows how densification is achieved during compaction and sintering. In the compaction portion the graph is relative density vs. compaction pressure whereas in sintering it is relative density vs. time.

Chapter 5

Results and Discussion

This chapter demonstrates for two sample parts various phases of the system as discussed in chapters *Systems Analysis* and *Implementation*. For **part I**, the powder is selected from the powder data base and for **part II**, no powder in the database for powder is found suitable and hence a new powder is read.

The underlined quantities on the right hand side indicate the value supplied by the user. Quantities enclosed in rectangular boxes represent the options selected by the user. The *italicized* quantities are the outputs of the system. As calculation proceeds the system prints the values of various quantities calculated over the stages. The final output appears at the end.

5.1   Part I : Solid Cylinder

5.1.1   Part Specification

Part type   : Solid Cylinder

Diameter of the part (in mm)   : 40.0

Length of the part (in mm)   : 35.0

Required Ultimate Tensile Strength (in MPa)   : 245.0

5.1.2   Powder Selection

Powders in the database can make the part (see section 4.3). The list of powders in the decreasing order of preference :

	Powder Name	Required relative density
1	Nickel	0.972
2	Copper	0.944

Select a powder from the above list :   Nickel

Mass of the powder required for each part : *380.5* gm.

5.1.3   Compaction

What is the minimum rise in percentage
densification per unit rise in pressure   :   0.5

What is the percentage
densification target (85 – 95)   :   93.0

Percentage densification target not reached and due to minimum density rise criteria the percentage densification reached is *86.1%* at pressure *60.0* MPa (see section 4.4.1).

Select one of the following options :

1. Neglect the criteria of minimum density rise and select pressure required to achieve the percentage densification target.

2. Input a new densification target and select the pressure required to achieve the target.

3. Select pressure according to minimum density rise criteria alone.

Option selected   :   2

Input new densification target :   <u>88.0</u>

Pressure selected   :   *65.43* MPa

Diameter of the die   :   *40.68* mm

Punch travel   :   *11.21* mm

Load required   :   *8.67* ton

Select a Press from the preferential list of able presses (see section 4.4.2).

Able press list :

$$P15,\ P20,\ P30,\ P50,\ P70,\ P100$$

Press selected : P15

5.1.4   Sintering

Enter Ambient temp. in deg. cels.   :   <u>27.0</u>

Enter Maximum Sintering temp. (in %)
(Default is 95.0% of Melting Point)   :   <u>88.0</u>

Enter Maximum acceptable sintering time (in minutes) :   <u>40.0</u>

Enter Minimum heating rate (in deg. cels./hr.)   :   <u>50.0</u>

Enter Maximum heating rate (in deg. cels./hr.)   :   <u>100.0</u>

Sintering unsuccessful (see section 4.5).

No cases obtained within the acceptable limits.

The options are :

1. Start from Sintering again.

2. Start from Compaction again.

3. Cancel the part.

Option selected : $\boxed{1}$

Enter Ambient temp. in deg. cels.   : <u>27.0</u>

Enter Maximum Sintering temp. (in %)
(Default is 95.0% of Melting Point   : <u>95.0</u>

Enter Maximum acceptable sitering time (in minutes) : <u>200.0</u>

Enter Minimum heating rate (in deg. cels./hr.)   : <u>50</u>

Enter Maximum heating rate (in deg. cels./hr.)   : <u>250</u>

Sintering successful (see section 4.5).

Total no. of acceptable cases : 234 (see section 4.5).

The higher the case no. the lower is the preference.

For selecting a case type the case no. and click $\boxed{\text{YES}}$ if satisfied.

Case selected   : <u>3</u>

5.1.5   Output

Diameter of the part   : *40.0* mm

Length of the part   : *35.0* mm

Diameter of the die   : *40.68* mm

Punch travel   : *11.21* mm

Mass of the part   : *380.5* gm

Powder name   : *Nickel*

Pressure selected   : *65.40* MPa

Press selected   : *P15*

Ambient temperature	:	$27.0\,^0$Cels.
Selected Sintering Temperature	:	$1000.0\,^0$Cels.
Selected heating rate	:	$245.0\,^0$Cels./min.
Sintering time	:	17.23 min.

Graphic Display

A crude simulation of the compaction and sintering processes that appears on the screen is symbolically represented in the following figures. The transformation of various stages is gradual. The figures show the longitudinal section of the part.

In the figures for sintering the inside rectangle with dashed boundary represents the final part to be made—a target for sintering. The outside rectangle is the part at some point of time while the sintering is on. The outside rectangle is deliberately made larger for a better appreciation of the transformation.

5.2   Part II : Hollow Cylinder

5.2.1   Part Specification

Part type	:	Hollow Cylinder
Outer Diameter of the part (in mm)	:	60.0
Inner Diameter of the part (in mm)	:	30.0
Length of the part (in mm)	:	40.0
Required Ultimate Tensile Strength (in MPa)	:	550.0

5.2.2   Powder Selection

Powders in the data base can not make the part (see section 4.3). Input a new powder ? : YES

A dummy powder is read to check the algorithm.

Upper Punch

Die

4068

58.02

Lower Punch

Part being prepared
for compaction

Upper punch approach
toward powder fill

Upper punch Just touching
the powder fill
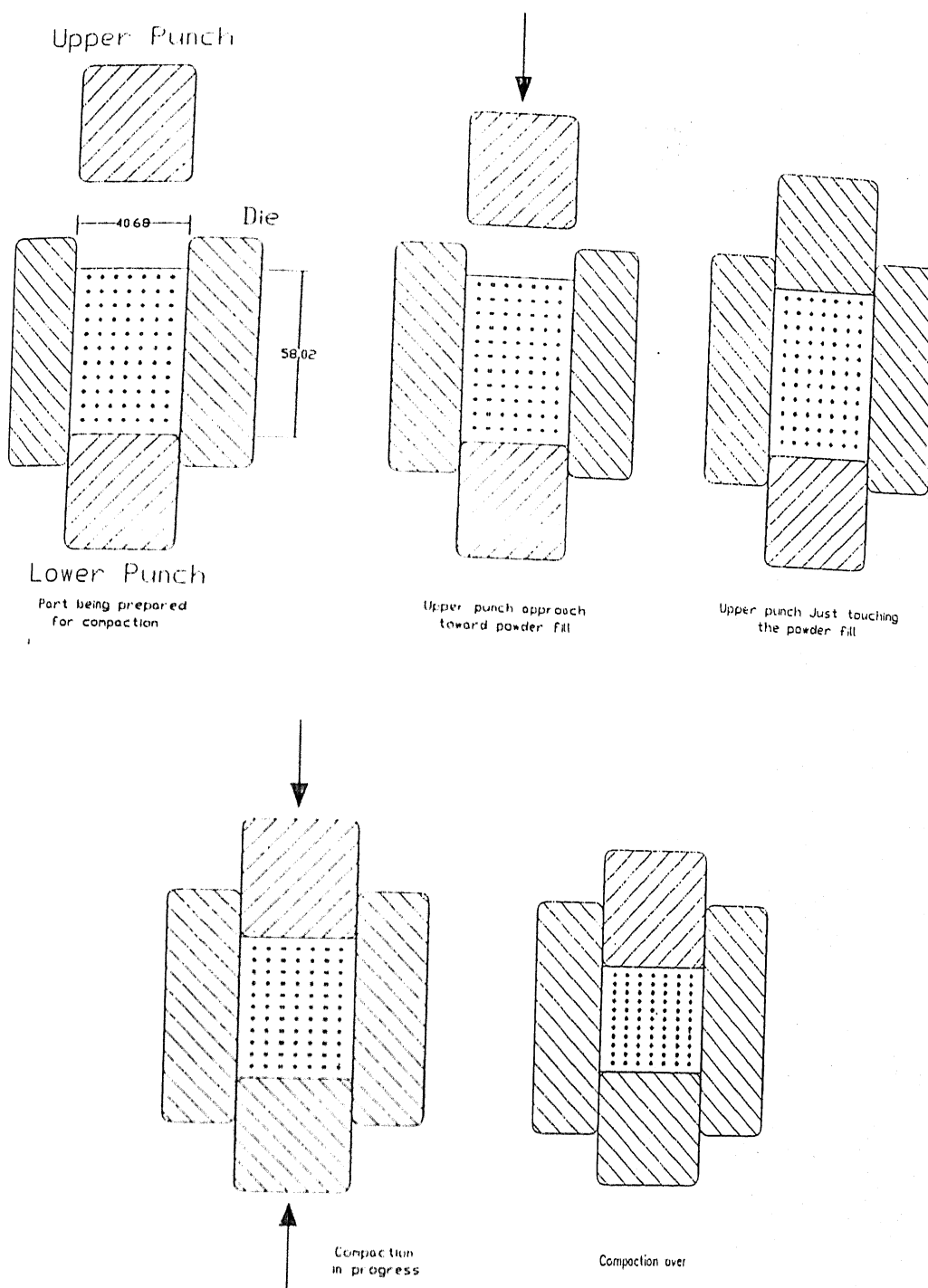
Compaction
in progress

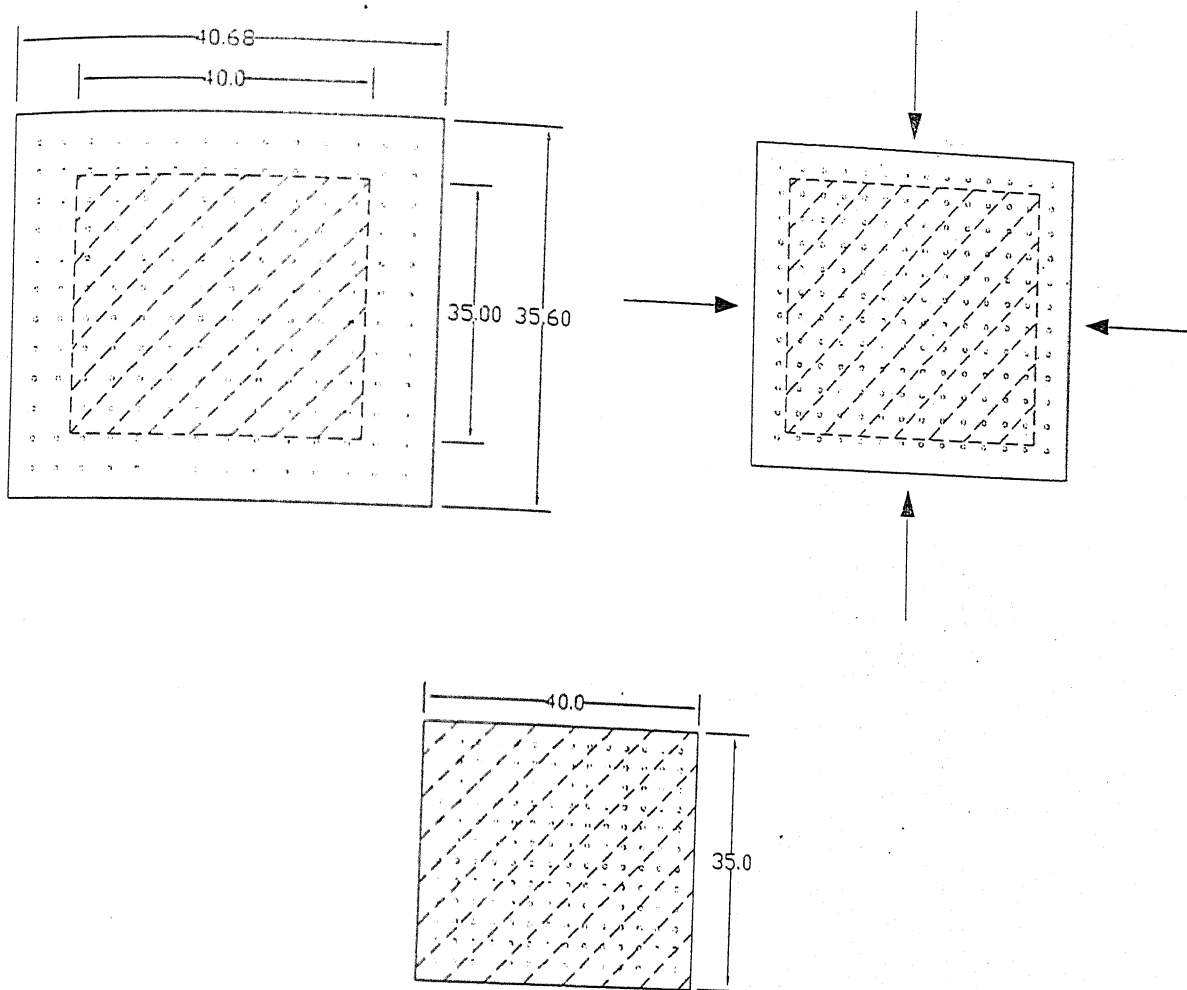Compaction over

Figure 5.1: Various stages of compaction.

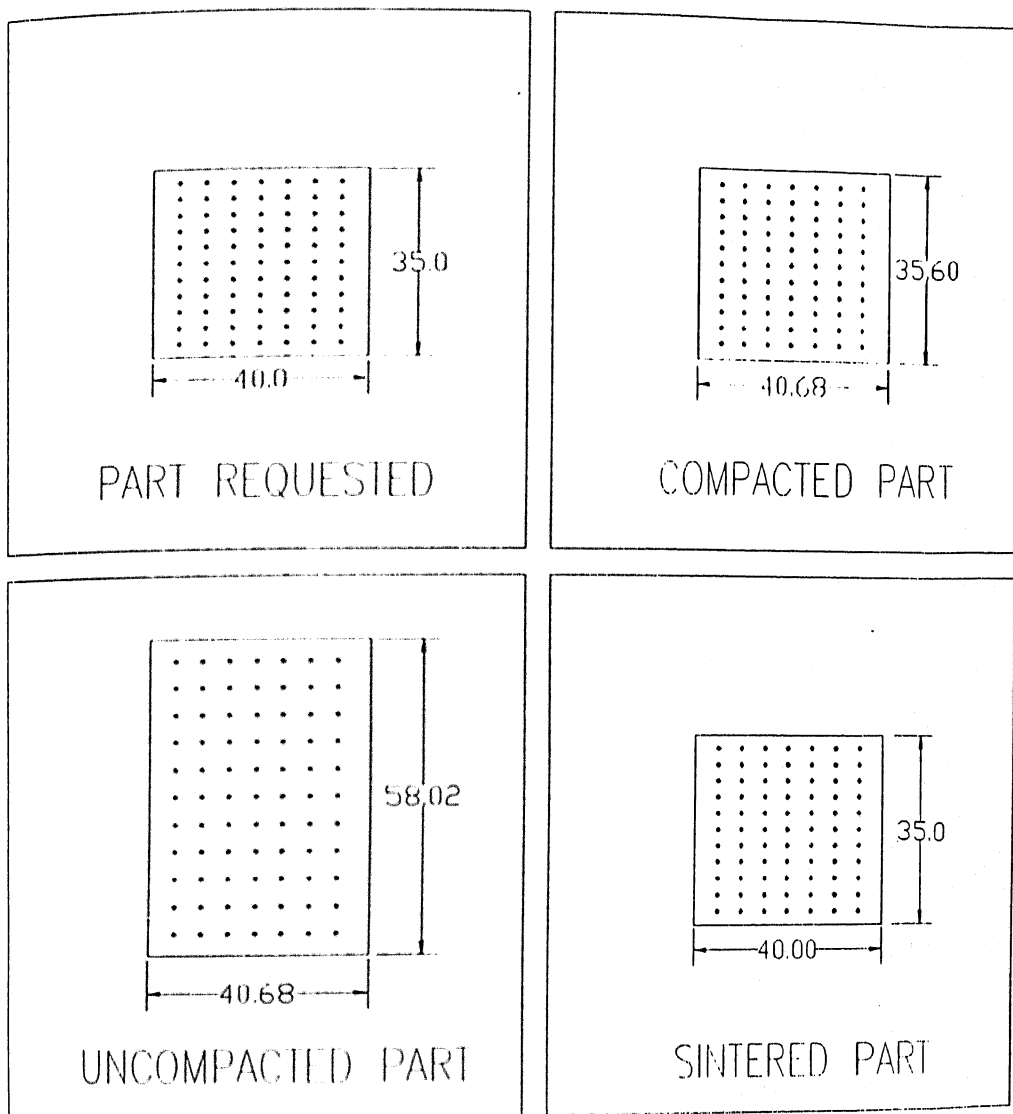Figure 5.2: Various stages in sintering.

Figure 5.3: Part dimension at various stages of P/M process.

2. Input a new densification target and select the pressure required to achieve the target.

3. Select pressure according to minimum density rise criteria alone.

Option selected	:	$\boxed{1}$
Pressure selected	:	*75.60* MPa
Diameter of the die	:	*60.6* mm
Diameter of the core rod	:	*30.3* mm
Punch travel	:	*14.0 mm*
Load required	:	*17.34* ton

Select a Press from the preferential list of able presses (see section 4.4.2).

Able press list :

P30, P50, P70, P80, P100

Press selected : $\boxed{P30}$

5.2.4   Sintering

Enter Ambient temp. in deg. cels.	: <u>28.0</u>
Enter Maximum Sintering temp. (in %) (Default is 95.0% of Melting Point)	: <u>95.0</u>
Enter Maximum acceptable sitering time (in minutes)	: <u>200.0</u>
Enter Minimum heating rate (in deg. cels./hr.)	: <u>50</u>
Enter Maximum heating rate (in deg. cels./hr.)	: <u>250</u>

Sintering successful (see section 4.5).

Total no. of acceptable cases : *374*

The higher the case no. the lower is the preference.

For selecting a case type the case no. and click YES if satisfied.

Case selected   : 5

5.2.5   Output

Outer Diameter of the part	:	*60.0* mm
Inner Diameter of the part	:	*30.0* mm
Length of the part	:	*40.0* mm
Diameter of the die	:	*60.6* mm
Diameter of core rod	:	*30.3* mm
Punch travel	:	*14.0* mm.
Mass of the part	:	*818.0* gm
Powder name	:	*xyz*
Pressure selected	:	*78.50* MPa
Press selected	:	*P30*
Ambient temperature	:	*28.0* °Cels.
Selected Sintering Temperature	:	*1100.0* °Cels.
Selected heating rate	:	*135.0* °Cels./min.
Sintering time	:	*17.75* min.

The graphic display part is similar to that of the previous part with the exception of a core rod for the hole to be made.

5.3 Discussions

As initially for **part I** we had fixed too less an acceptable sintering time limit, so within that period densification resulting from sintering was insufficient. With the initial set of confining boundaries the solution space was an empty set. When we restarted the sintering process the confining boundaries were made liberal and the solution space no longer was an empty set.

For **part II** the required ultimate tensile strength was so high that powders available in the data base were unable to impart such strength in their products. The initial part of the run for part II is actually the data addition module.

The prime objective of the current work is to evolve a methodology to select in advance some process parameters. The results shown in this chapter are merely an indicative of the algorithm discussed in the chapter *Systems Analysis* and *Implementation.*

Chapter 6

Summary

The present chapter gives a summary of the present work and a discussion of its limitations which may be taken up in future work.

6.1 Present Work

The major objective of the current work was to interlink the various stages of powder metallurgy process. Useful relations from among immense scattered literature was found out that may contribute to the prediction of the generalised behaviour. Because of the vast scope, all parts of the problem did not get the proper attention they deserved.

The emphasis was to set up a structure toward tackling the problem as a whole instead of concentrating on a particular aspect of the process. The elaboration of a particular part can be easily fitted to the main structure. Work was limited to *DSS*. To develop a full fledged *CAPP*, much larger database is needed. Experiments may have to be carried out extensively focussing on the general behaviour of the powder as the process advances.

6.2 Limitations

The major limitation of the current work is the unavailability of structured data. Immense literature is available on Powder metallurgy and on each of its stages. But the emphasis is on its microscopic aspect – the mechanism of why something happens, rather than on a general behaviour on the macroscopic level. One reason for this is, the process is extremely complicated and the process characterizing factors are too many. Empirical relations galore, but they are too limited to a certain system under certain conditions. The following is a discussion on the limitations of the current work and how it can be expanded.

6.2.1 Powder Selection

The selection criteria for a powder discussed here is based on the ultimate tensile strength of the part to be made. The actual selection criteria should depend on the use of the part. When the operating temperature is high, creep rate may be the right selection criteria. When the part is subjected to cyclic load the right criteria may be the fatigue limit, just as the ultimate tensile strength may be the right criteria when the loading is static and the operating temperatures are not too high.

6.2.2 Binder Selection

Fine powders prove difficult to press. Consequently, large agglomerates are formed to aid flow. The powder is mixed with an organic and a volatile agent to form a slurry. The slurry is sprayed into a heated free–fall chamber where surface tension forms spherical agglomerates. Heating of the agglomerate during free–fall causes vaporisation of the volatile agent giving dense packed agglomerate. Selection of binder depends on the powder selected. After powder selection, binder can be selected accordingly by having some rules.

6.2.3   Compaction

Part Shape

The current work revolves around two kinds of simple cylindrical shapes—the solid cylinder and the hollow cylinder. Actually the powder metallurgy products far from being so simple are usually very complicated in shape. In such complicated shapes tooling design becomes very important. A separate module for tooling may be attached to the compaction module to take care of such complicated shapes.

Frictional Effect

The effect of friction has been ignored in the current work. The consideration of friction also brings into picture lubrication during compaction. This can be taken up in the future work.

6.2.4   Sintering

The current work is limited to single phase powders. The relations used in sintering holds only for single phase powders. Powder metallurgy is normally used to obtain products having special properties. To obtain these properties powders are used which are very often not single phase powders.

Sintering Atmosphere

Selecting a particular atmosphere for sintering metal powders is important. Most all metals require some form of protection from oxidation during sintering. Oxides on the powder surface hinder diffusion bonding and the development of adequate properties. The atmosphere may also prove useful in removing lubricants and binders used in compaction. The current work does not take into account this consideration and accordingly this can be included in future work.

6.3 Scope for Future Work

The field of powder metallurgy is so vast that there is no end to the extension that can be carried out. Some of the immediate extensions to this work are listed as below :

1. Generalised powder selection criteria depending on the use of the part may be incorporated.

2. A binder selection module may be added.

3. A tooling design module may be inserted in the compaction module.

4. Friction consideration may be added.

5. It can be expanded to multiphase powders.

6. The effect of sintering atmosphere may be taken care of.

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Appendix

Various constants used in the calculation :

Powder	E_a (cal/gm-atom)	E_b (cal/gm-atom)	a/b	Solid density (gm/cc)	Melting Point ($^\circ C$)
Copper	48400.0	62700.0	1.095×10^{-2}	8.96	1083.0
Nickel	72000.0	95000.0	8.06×10^{-4}	8.90	1453.0
Silver	54000.0	73000.0	1.15×10^{-3}	10.49	961.0